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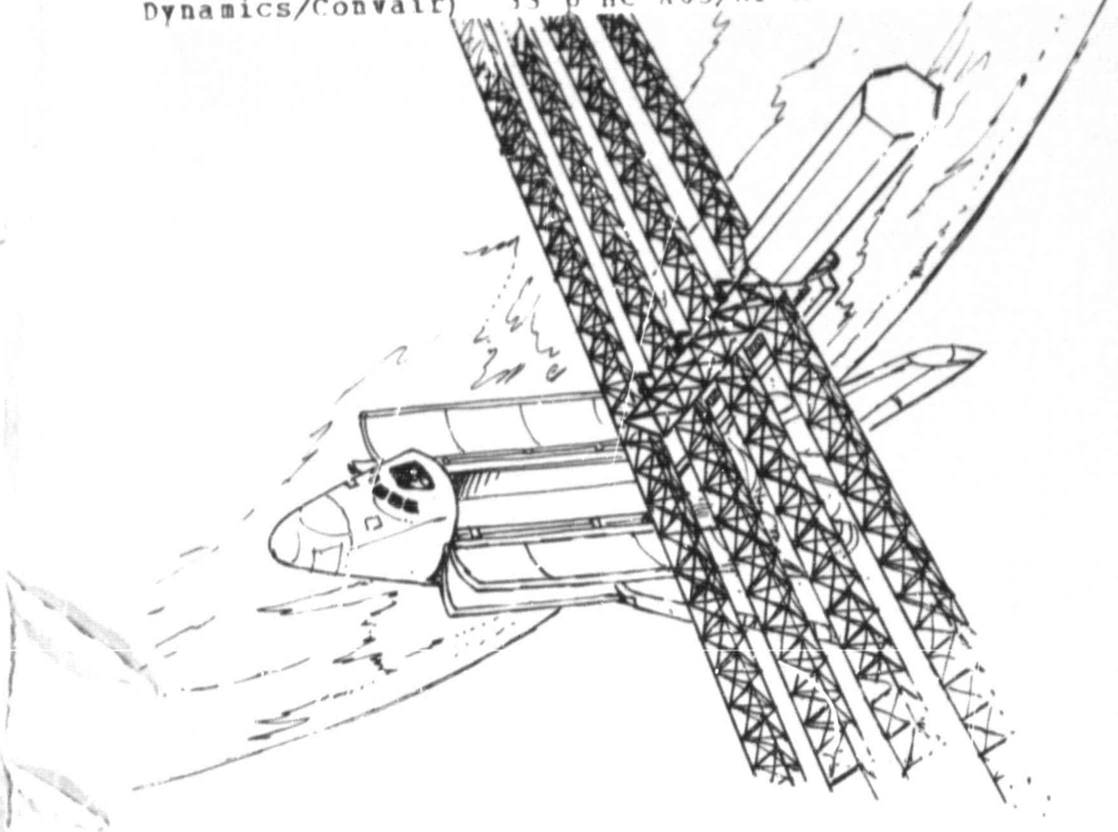

SPACE CONSTRUCTION AUTOMATED FABRICATION EXPERIMENT DEFINITION STUDY (SCAFEDS) PART III

FINAL REPORT
VOLUME I • EXECUTIVE SUMMARY

CONTRACT NO. NAS9-15310
DRL NO. T-1346
DRD NO. MA-664T
LINE ITEM NO. 3

GENERAL DYNAMICS
Convair Division

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Advanced Space Programs

CASD-ASP78-016

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29 June 1979

Submitted to
National Aeronautics and Space Administration
LYNDON B. JOHNSON SPACE CENTER
Houston, Texas 77058

Prepared by
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FOREWORD

This final report was prepared by General Dynamics Convair Division for NASA-JSC in accordance with Contract NAS9-15310, DRL No. T-1346, DRD No. MA-664T, Line Item No. 3. It consists of three volumes: (I) a brief Executive Summary; (II) a comprehensive set of Study Results; and (III) a compilation of Requirements.

The principal study results were developed from August 1978 through April 1979, followed by final documentation. Reviews were presented at JSC on 13 December 1978 and 24 April 1979, and at NASA Headquarters on 17 May 1979.

Due to the broad scope of this study, many individuals were involved in providing technical assistance. General Dynamics Convair personnel who significantly contributed to the study include:

Study Manager	Lee Browning
Mechanical Design	John Bodle, Steve Hardy, Hans Stocker
Avionics & Controls	Jack Fisher, Ed Kleidon, Bill Snyder, Doug Burgess
Requirements	Jim Peterson
Development Plans	John Maloney
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Structural Dynamics	Des Pengelley, Shih-How Chang
Thermodynamics	Dick Pleasant
Mass Properties	Dennis Stachowitz
Mfg. Technology	Steve Hardy
Economic Analysis	Bob Bradley
Test Integration	George Copeland

The study was conducted in Convair's Advanced Space Programs department, directed by J. B. (Jack) Hurt. The NASA-JSC COR is Lyle Jenkins of the Spacecraft Design Division, under Allen J. Louviere, Chief.

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1

INTRODUCTION

1.1 SCOPE

This Executive Summary is one of three volumes comprising the SCAFED Study Part III Final Report. Other volumes provide the detailed results of all study tasks and an updated comprehensive Requirements Document. A corresponding 3-volume set was prepared at the conclusion of the Part I/II study effort in May 1978. Parts I/II and III fully document all SCAFEDS effort to date.

1.2 STUDY OVERVIEW

1.2.1 PART I/II SUMMARY. In Part I/II a wide range of tasks was focused on a baseline system concept as shown in Figure 1-1. A beam builder concept was developed to produce the triangular beam shown. Beam elements used laminated graphite and glass composite strip material with external surface coatings.

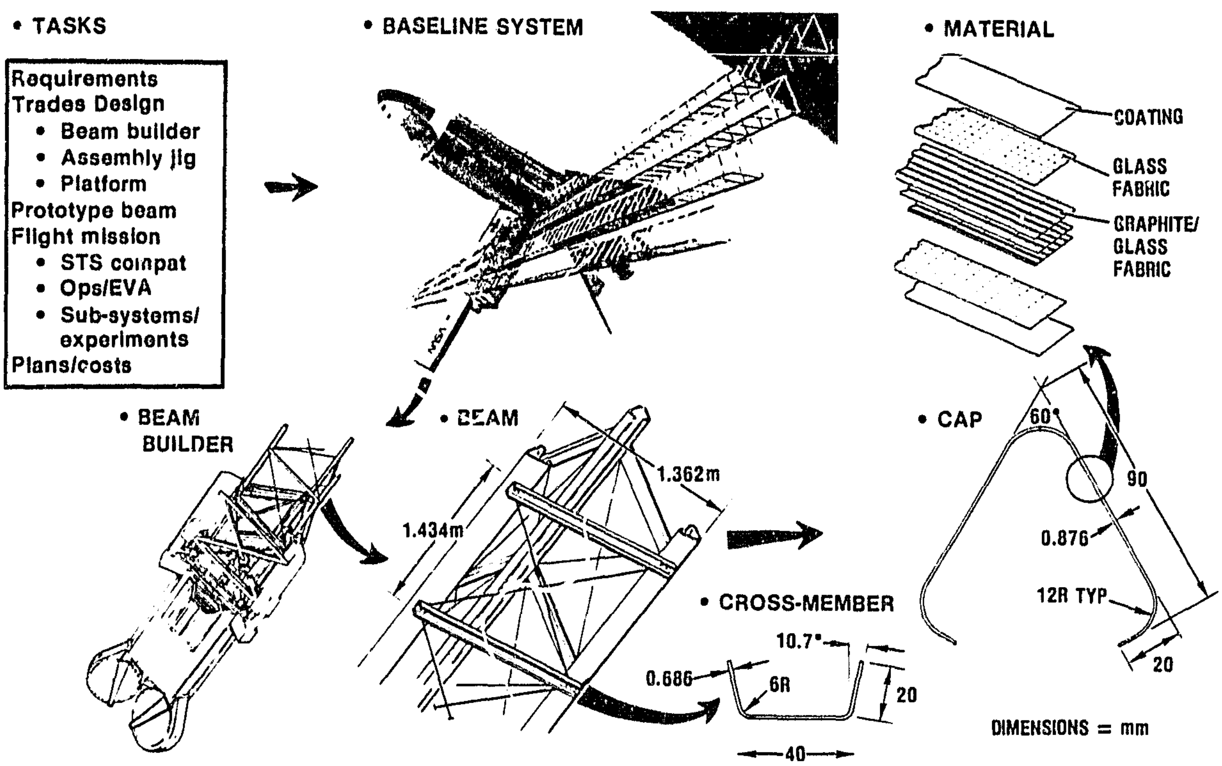


Figure 1-1. Part I/II summary.

1.2.2 PART III TASKS. Part III major task groups build on inputs from Part I/II and relate to each other per the flow illustrated in Figure 1-2. Each major Part III task group is divided into subtasks as shown in Figure 1-3. In Task III the five subtasks were performed, as appropriate, for each of the six alternative structural arrangements shown.

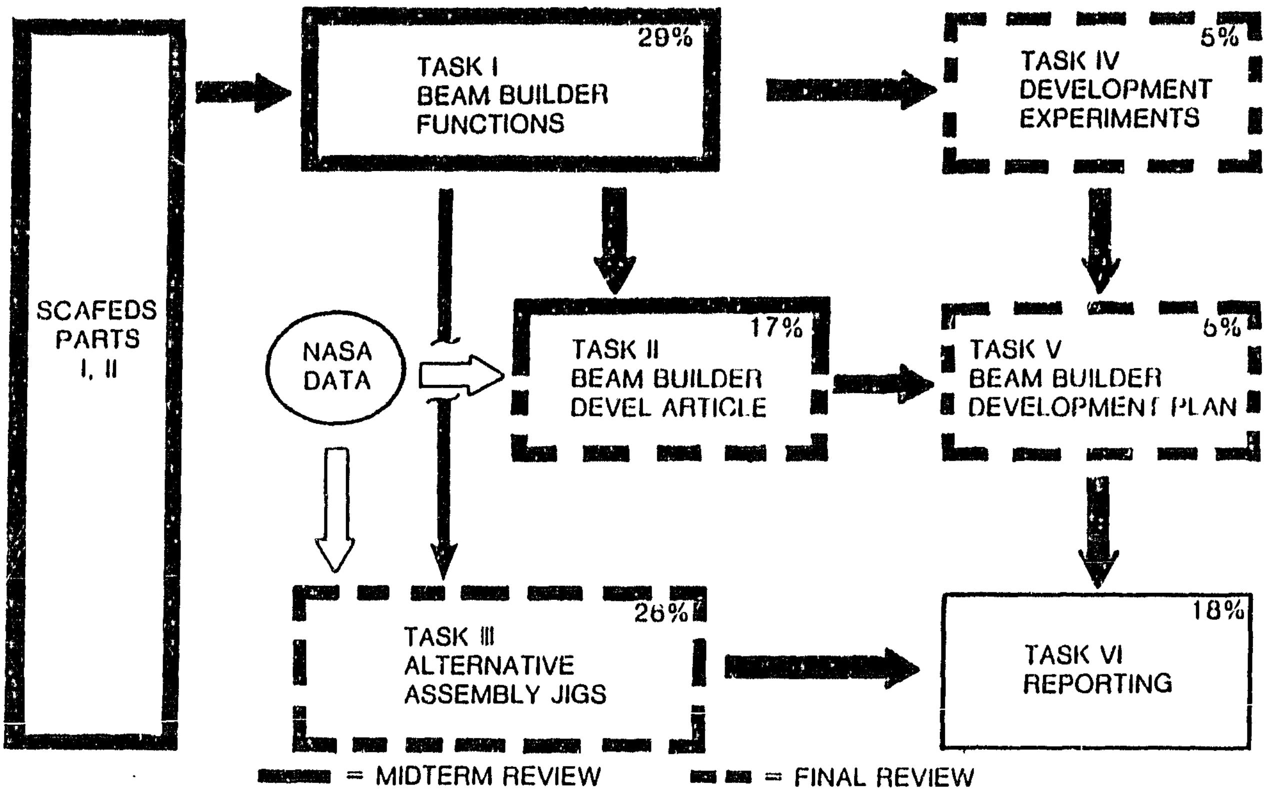


Figure 1-2. Part III task relationships.

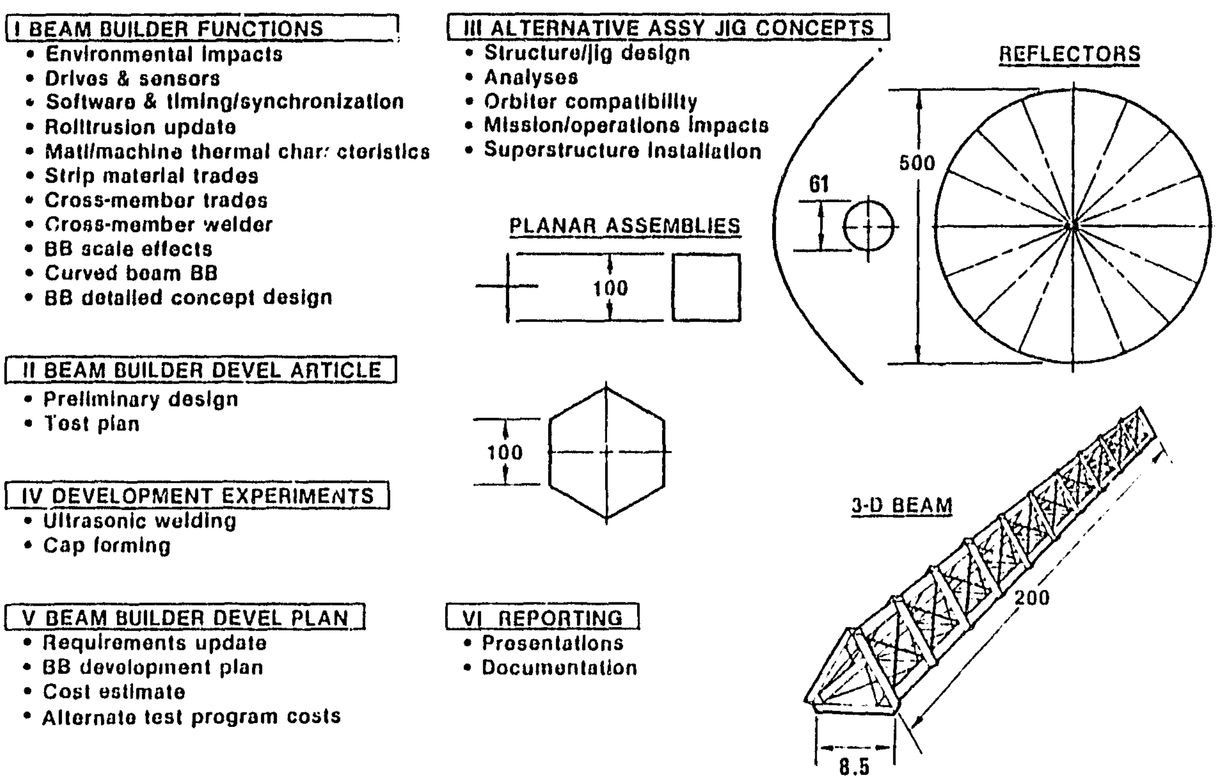


Figure 1-3. Part III detail tasks.

2

STUDY RESULTS

2.1 BEAM STRUCTURE/MATERIALS

The Part I/II structural design effort developed a baseline experimental "ladder" platform using a triangular beam concept selected as a result of an integrated beam and beam builder trade study. The ladder platform and the overall beam size/arrangement were retained as program baselines for Part III. However, new materials evaluations and machine/material compatibility considerations have since led to: (1) selection/optimization and prediction of the thermal characteristics of a new single-ply strip material; and (2) trades and selection of both an improved cross-member section and improved weld joint configuration for joining cross-members and cords to the beam caps.

2.1.1 NEW STRIP MATERIAL. During the Part I/II effort, a "multi-ply" laminated material design evolved which combined the benefits of glass and graphite fibers, thermoplastic resin, and a pigmented resin coating into a strip material suitable for the SCAFE fabrication process and service environments. However, the benefits to be achieved by combining the desirable features of the constituent materials into a single-ply woven strip were already recognized, and are summarized in Figure 2-1. Private development effort has since led to a material in which the anticipated processing/property/forming benefits of single-ply construction have been realized and this approach has been adopted for the SCAFE application. Since the ply thickness and stacking symmetry constraints of the laminate approach are eliminated in the single-ply approach, the principal objective in further strip material optimization was weight reduction via cap gage decrease, while maintaining both beam natural frequency and a "comfortable" margin of ≥ 2.0 against local instability.

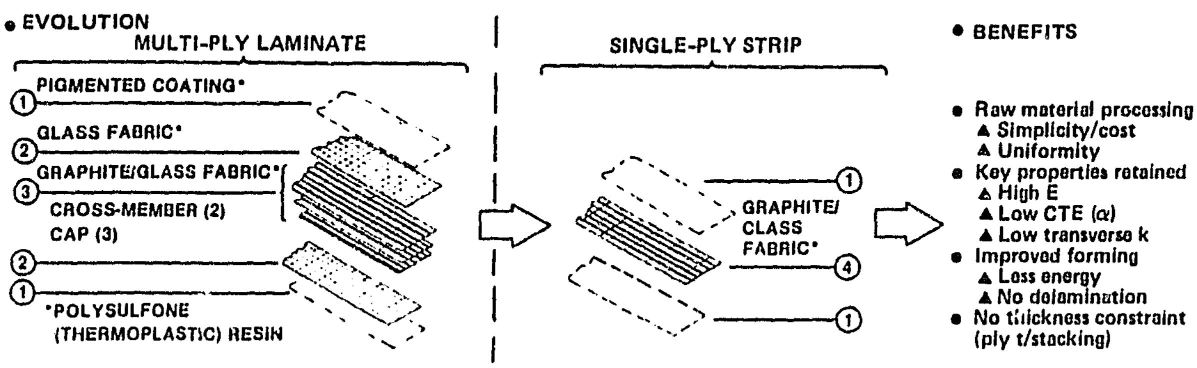


Figure 2-1. Strip material evolution and benefits.

A new, thinner material, providing increased stiffness, significant weight decrease, a small but acceptable frequency penalty, and a large local stability margin has resulted. Cap/cross-member material commonality has been achieved with this material being used in the new cross-member design discussed below.

2.1.2 MATERIAL THERMAL CHARACTERISTICS. The value of overall effective thermal conductivity in the thickness direction is required to determine the temperature

difference between the strip top and bottom surfaces as the material passes between the heaters and the temperature sensors. The overall laminate thermal resistance is equal to the sum of four "layer" resistances based on the material idealization of Figure 2-2. Using individual "layer" conductivities of 0.904, 0.206, and 0.260 W/m-K for the graphite, glass, and coatings, respectively, the calculated effective conductivity of the total strip is 0.484 W/m-K. Strip conductivity is independent of the weave and has a low sensitivity to the graphite fiber conductivity. Calculations indicate that the strip thickness-direction ΔT in the heating section will be between 3 and 6 C.

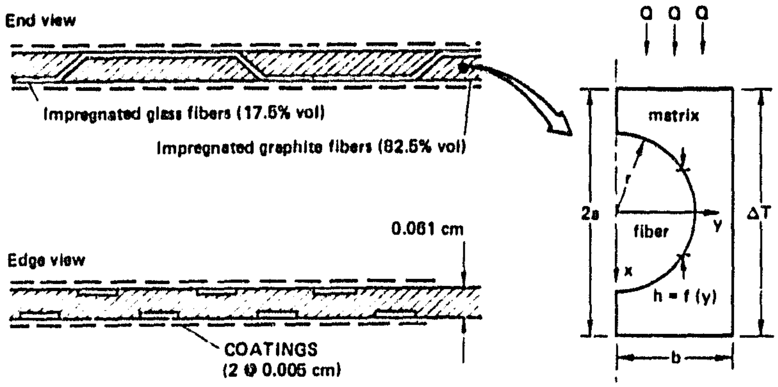
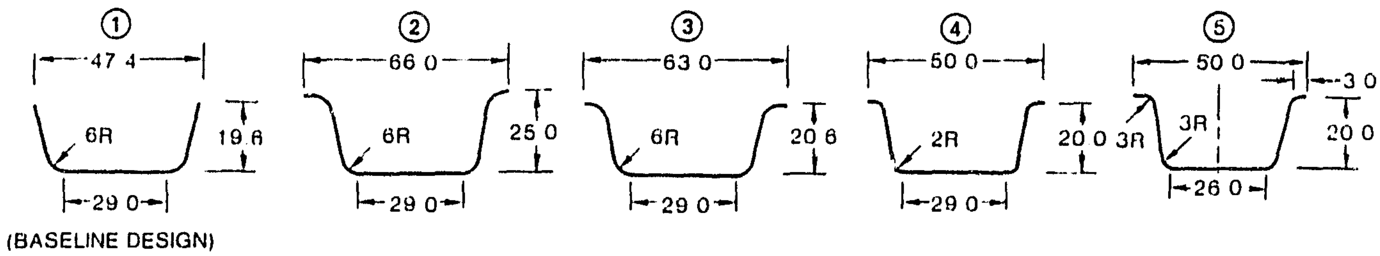


Figure 2-2. Consolidated strip material cross-section.

2.1.3 CROSS-MEMBER TRADES. The cross-member trade study was conducted to both improve the reliability of mechanized handling by the clip feed subsystem and to increase the structural capability of the cross-section for differential drive. A lipped-channel section was selected since it met both objectives. Configuration and evaluation results of the original simple channel and several lipped-channel alternatives are summarized in Figure 2-3. The selected section shares a common material with the beam caps, is 5% heavier (due to perimeter increase), exhibits a sidesway end-moment capability of 30.0 Nm (vs. 1.9 Nm before) and fits the same clip external envelope.



FEATURE	EVALUATION				
Configuration	①	②	③	④	⑤
Material*	A	B	B	B	B
Mass (kg/m)	0.075	0.102	0.091	0.081	0.079
Beam column M.S.	1.75	2.12	1.82	1.35	1.29
M_{max} (N-m)	1.9	54.6	45.3	28.0	30.0
Mechanism compat.	Poor	Good	Good	Better	Best
Selected Design					✓

*Material: A: Original laminate, t = 0.584mm, E = 128.7 GN/m^2
B: Single ply, t = 0.635mm, E = 117.9 GN/m^2

Figure 2-3. Cross-member trade/selection.

2.1.4 WELD JOINT TRADES. The weld joint pattern trade was initiated primarily to evaluate the in-plane and moment resistance necessary for differential drive, and secondarily to assess the increase in welding power required for larger area weld patterns. Figure 2-4 compares the baseline weld pattern (U_1/L_1) with various alternative concepts for the upper (U) cap/cross-member weld(s) and the lower (L) cap/cross-member/cord weld in terms of spot quantity, size, spacing, cord capture geometry, pattern width, and moment capability. The selected weld pattern geometry U_1/L_2 is quite similar to the initial pattern with a slight area reduction. Its moment capacity is less than that of the cross-member (30.0 Nm) but is easily increased, if needed, by a simple change to the U_3/L_2 pattern as shown.

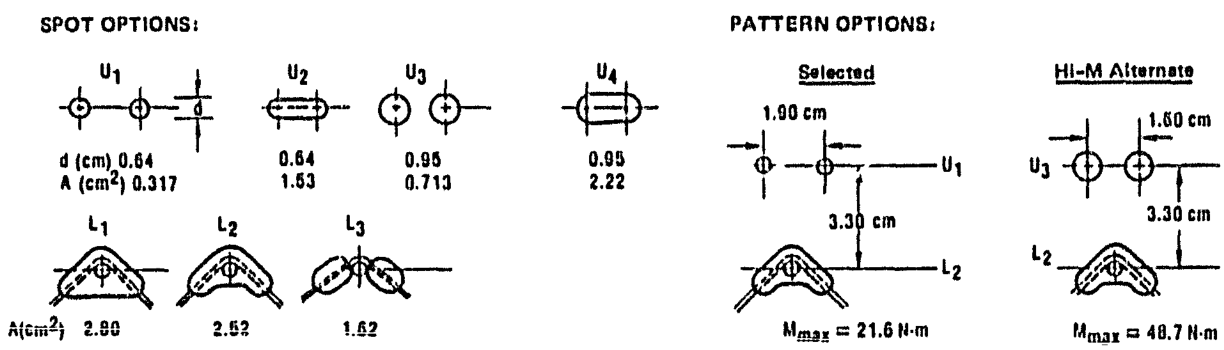


Figure 2-4. Weld joint trade.

2.1.5 BEAM CHARACTERISTICS. As a result of the selection of a new strip material and a new cross-member section, several beam and beam element characteristics have changed. Although the overall beam dimensions remain unchanged, new values have been computed for both the mass and all mechanical properties except torsional stiffness, KG. The stiffness is unchanged, since the previous bay geometry and cord design have been retained. Figure 2-5 summarizes the updated characteristics of the beam assembly, cap, and cross-member.

2.2 BEAM BUILDER DESIGN

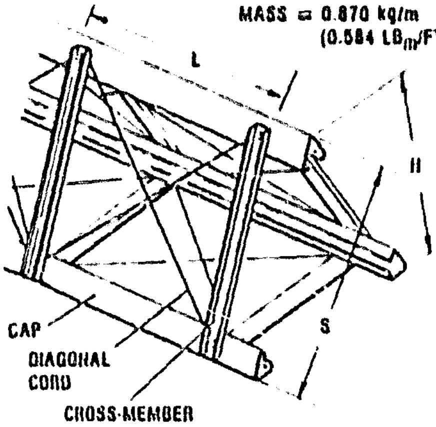
Preliminary design and analysis and design trades were conducted on structural, mechanical, and controls details of the SCAFEDS Part II beam builder conceptual design. These analyses and trades defined a beam builder development configuration and identified critical design criteria for compatibility with Space Shuttle payload operational, environmental, and safety requirements.

2.2.1 BEAM BUILDER CHARACTERISTICS. Updated characteristics of the baseline beam builder are summarized in Figure 2-6. The length has increased 0.56 m to accommodate subsystem update changes. The estimated mass (launch weight for SCAFE mission) is now 214 kg less based on updated materials and subsystem design data. The new strip material is incorporated in the productivity data; however, the energy and rate values have not changed.

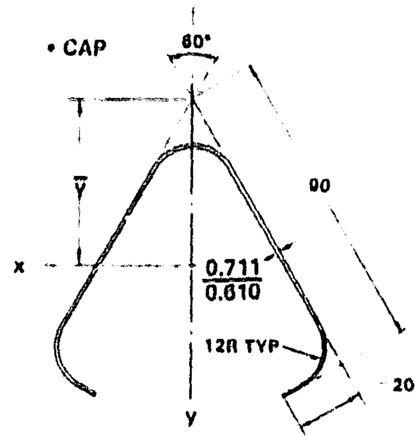
2.2.2 DRIVES AND SENSORS. The baseline beam builder conceptual design identified the need for numerous electromechanical drives and controls sensors. The Part III

PHYSICAL

L = 1.434m
H = ·160m
S = ı.382m
MASS = 0.870 kg/m
(0.584 LB_m/FT)



• CAP

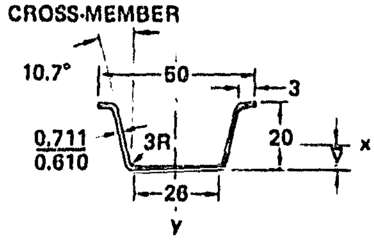


A	1.1½ cm^2	0.180 in^2
$\bar{y}$	48.67 mm	1.916 in
I_x	6.43 cm^4	0.155 in^4
I_y	8.117 cm^4	0.216 in^4
ρx	23.52 mm	0.926 in
ρy	27.79 mm	1.094 in

MECHANICAL

AE	-4.586 E7 N	1.031 E7 LB_f
I	1.078 E4 cm^4	2.591 E2 IN^4
EI	1.420 E7 $N \cdot m^2$	4.949 E9 LB_f IN^2
KG	1.111 E4 $N \cdot m^2$	3.871 E6 LB_f IN^2

• CROSS-MEMBER



A	0.48 cm^2	0.075 in^2
$\bar{y}$	7.85 mm	0.309 in
I_x	0.28 cm^4	0.008 in^4
I_y	1.25 cm^4	0.030 in^4
ρx	7.32 mm	0.288 in
ρy	16.10 mm	0.634 in

Figure 2-5. Updated beam and element characteristics.

• MASS: 3,404 kg

• PRODUCTIVITY

ENERGY: 160.5 kJ/BAY
RATE: 80 SEC/BAY

$\dot{L}$ = 1.08 m/MIN (3.53 FT/MIN)
$\dot{M}$ = 0.934 kg/MIN (2.06 LB_M/MIN)
P_{AVG} = 2,006W

$\dot{L}/P$ = 0.0892 m/kJ (105.4 FT/kWH)
$\dot{M}/P$ = 0.0078 kg/kJ (61.7 LB_M/kWH

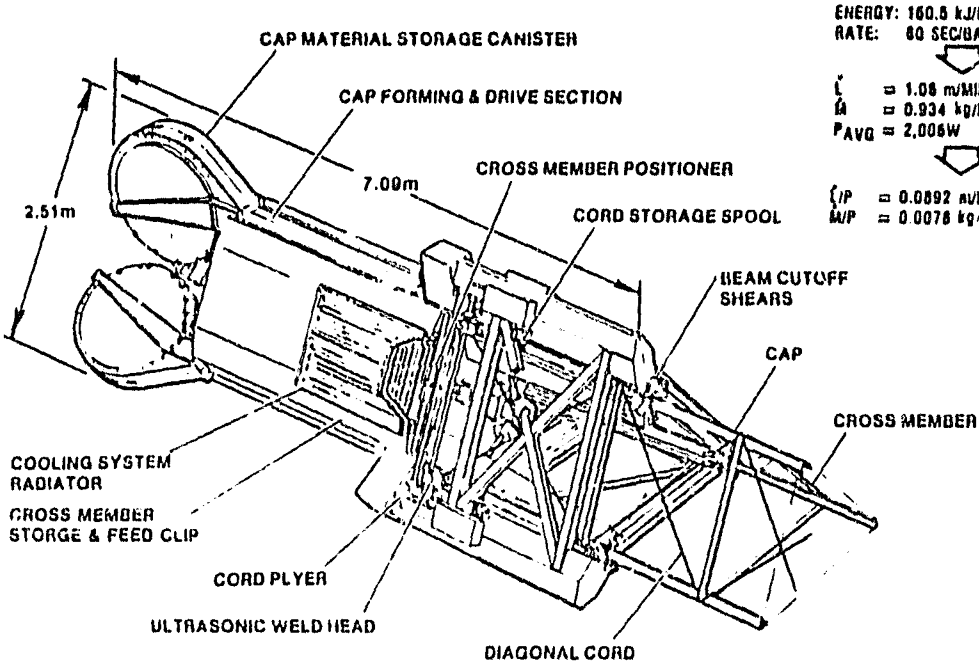


Figure 2-6. Beam builder characteristics update.

study included tasks to define and select electromechanical drives and sensors for the beam builder functions. This definition also required identification of special materials, lubricants, and environmental protection techniques. Finally, the subsystem and system design concepts were refined and analyzed to minimize the overall number of drives and sensors and to use common elements for cost-effectiveness where practical.

The most commonly used sensors and the most critical sensors were analyzed and trades performed on various candidates of each type to select the sensor technologies best suited for beam builder applications. The sensing technologies selected are summarized in Table 2-1. The strip heating and temperature sensing concept is illustrated in Figure 2-7.

Table 2-1. Sensor trade results.

Measurement	Selected Sensor Technology
Temperature	Thermopile
Current	Hall Effect Generator
Discrete Position	Hall Effect (proximity or vane)
Linear Position (screw drive)	Optical Rotary Shaft Encoder
Rotary Position	Optical Rotary Shaft Encoder
Force	Load Cell
Cap Travel	Encoded Magnetic Tape & Reader Head

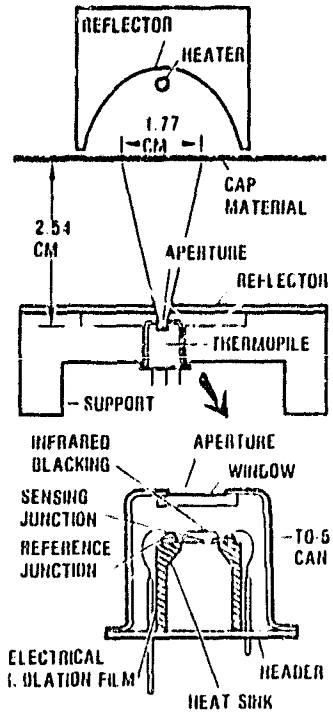
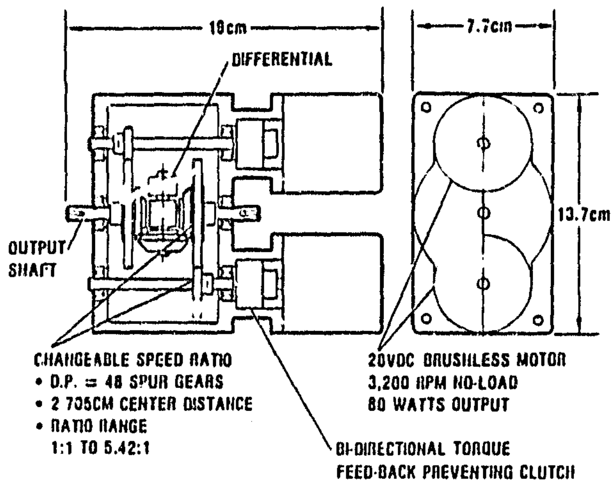


Figure 2-7. Thermopile installation concept.

The use of a single drive motor to meet all driving requirements in the beam builder has a significant cost advantage in procurement, test, and logistics. In order to evaluate the feasibility of using a common drive motor, a baseline dc brushless motor was selected which appeared to have adequate power to accomplish all of the drive functions within acceptable time limits. A concept for a dual motor drive unit, which would be adaptable to nearly every drive application, was designed. It was found that use of a common motor would satisfy all drive requirements, and that by applying the universal drive unit concept to each drive function, a significant reduction in the total number of drive elements could be achieved as seen in Figure 2-8.

2.2.3 PRELIMINARY SUBSYSTEM DESIGN. The preliminary subsystem design effort produced a detailed definition of all drives, mechanisms, and subsystem modules. It also produced definitions of all control subsystem elements to the block diagram level, timing and synchronization timelines for beam builder operations, and a breakdown of executive software elements, as illustrated in Figure 2-9.

The cross-member subsystem is an example of the work done to minimize the number of motors and incorporate common drive elements. Design trades of each element of the subsystem were performed which resulted in a final configuration, shown in Figure 2-10, that employs only two universal drive units (UDUs). One central drive unit operates the feed mechanisms on all three storage and feed clips. The second UDU operates three handlers, three positioner arms, and the positioner carriage. The handler/positioner operations are sequenced using electromagnetic particle clutches.



Subsystem Drives	Speed Ratio	Peak Motor Torque (S2) (Oz-In.)	UDU Speed Reduction	No. Motors Required
Forming				
• Cooling platen	10	59	N/A	6
• Cap	124	18	3:31-1	6
Crossmember				
• Clip feed	347	18	10.84:1	2
• Handler	353	18	7.06:1	2
• Positioner rotate	1,236	40		
• Positioner translate	8.4	30		
Cord				
• Aft cord plyer	15	40	10.32:1	2
• Forward cord plyer	15	40	10.32:1	2
Joining				
• Weld anvil	7.1	40	7.08:1	2
• Weld head positioner	108.4	80	10.84:1	6
Cutoff				
• Cap cutter	4.2	5	4.16:1	6
			Total	34

Note: Count includes redundant motors.

ELIMINATED 28 MOTORS AND SOLENOIDS

Figure 2-8. Results of drive commonality analysis.

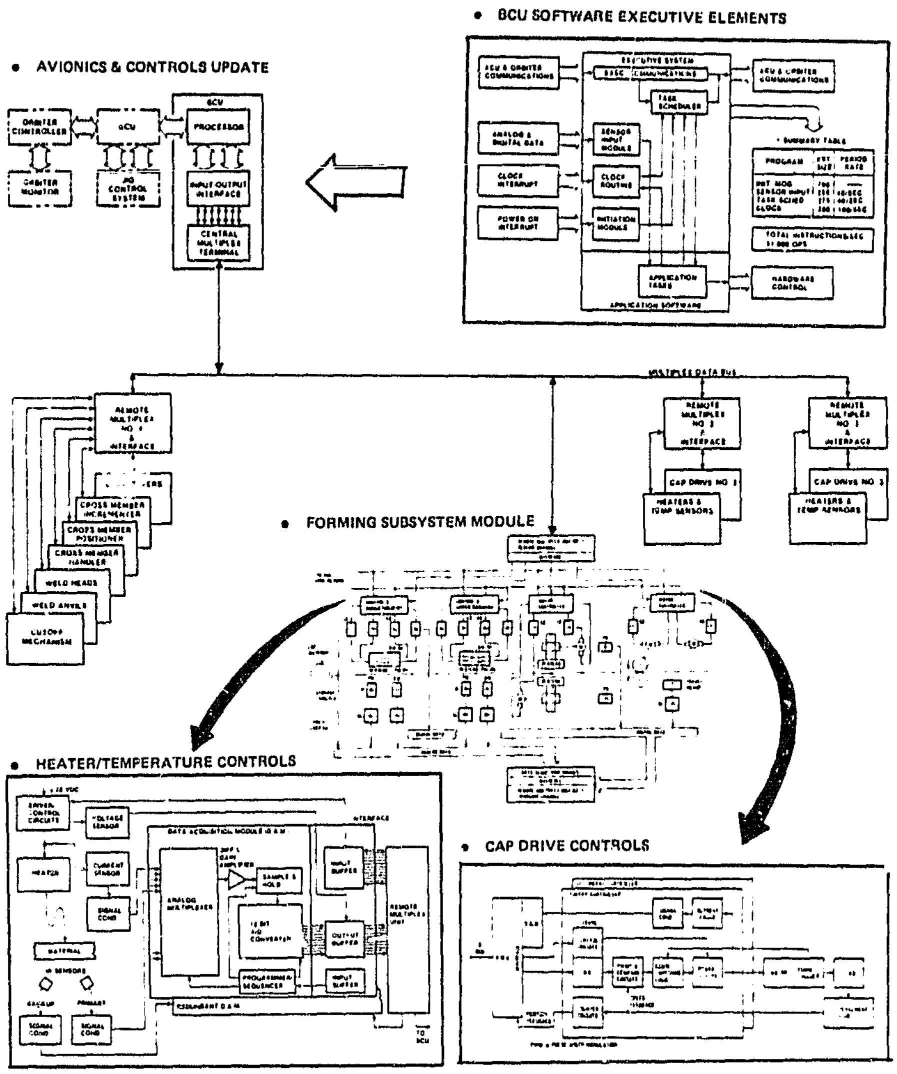


Figure 2-9. Controls and software definition.

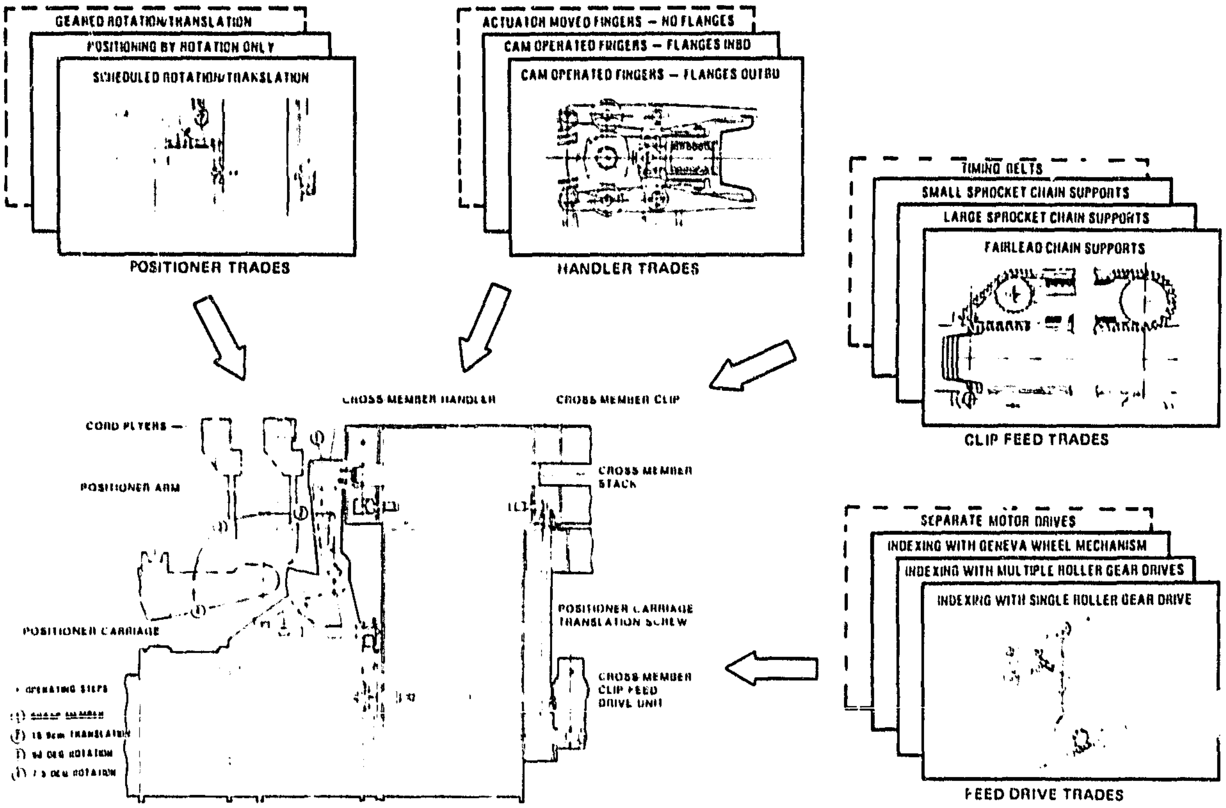


Figure 2-10. Cross-member subsystem preliminary design.

Another major subsystem preliminary design task was performed on the joining subsystem, which consists of six ultrasonic welders, three welder positioning mechanisms, one anvil drive mechanism, and associated controllers. The welder mechanism design is shown in Figure 2-11. The welders used in the preliminary design are 20-kHz units with multi-spotweld horns designed to produce the selected weld joint configuration shown in Figure 2-4. A review of current ultrasonic welding technology indicates that further reductions in the size and weight of the weld head are feasible, as shown in the upper portion of Figure 2-11.

Automated ultrasonic welding process control is accomplished by feedback control of critical weld parameters shown in the lower portion of Figure 2-11. Variations in weld horn natural frequency due to temperature change are monitored and the driving frequency is modulated to match the weld horn resonant frequency. The efficiency analyzer reads energy going into the material by comparing input energy to that reflected from the horn tip. This device automatically adjusts weld time to ensure that each weld receives an equal amount of energy. This verifies the quality of each weld in process.

2.2.4 ENVIRONMENTAL IMPACTS. An evaluation of the impacts of the Shuttle Environmental Design Requirements on beam builder hardware design was conducted. The component operating and nonoperating design criteria were first developed and the life duty cycles were defined, based on a single SCAFE mission.

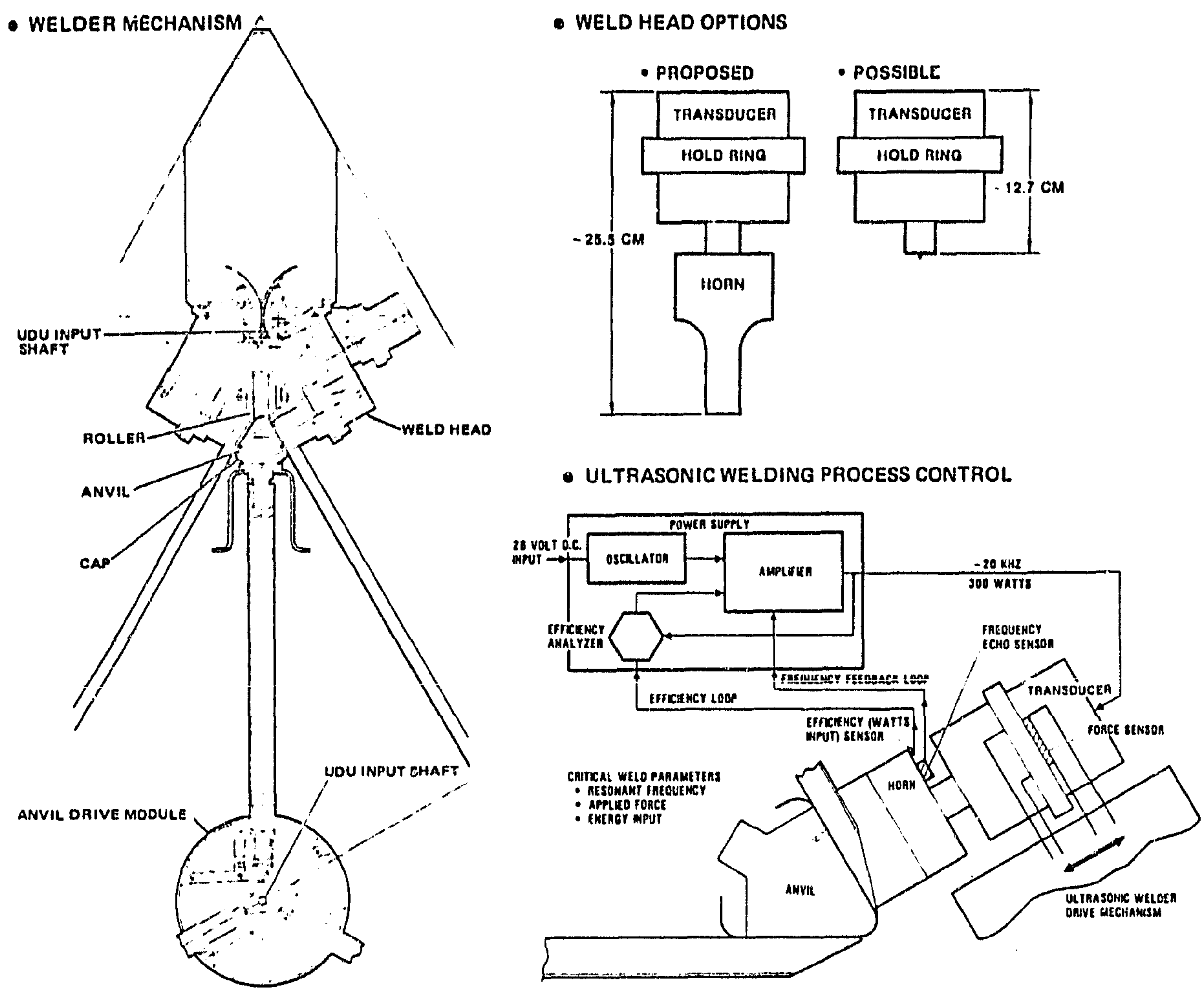


Figure 2-11. Joining subsystem design and evaluation.

From the preliminary design configuration, a listing of each of the basic subsystem components was compiled and the fundamental types of devices used in the mechanical and electronic hardware were identified. Using the environmental design criteria as applied to the individual subsystem components, the principal concerns were identified and general recommendations which deal with each of these concerns were compiled, as shown in Figure 2-12. This evaluation revealed no major problems. Thermal distortions in the support structure and modular beam-building subsystems can cause significant distortions in beam alignment during the assembly process. The structure shroud concept shown in Figure 2-12 eliminates this problem by completely covering the assembly process area with a multilayer insulation (MLI) blanket of aluminized mylar. Velcro strips are used to attach the MLI blanket to the external support structure. These simple attachments provide easy installation and immediate access to inspect and maintain any of the assembly subsystems.

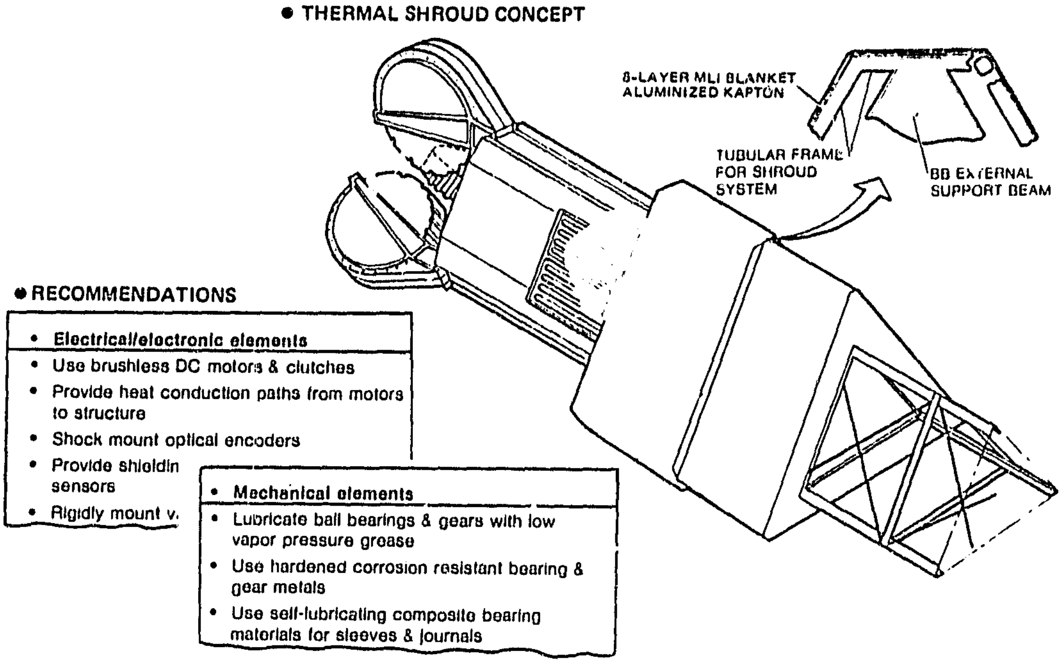
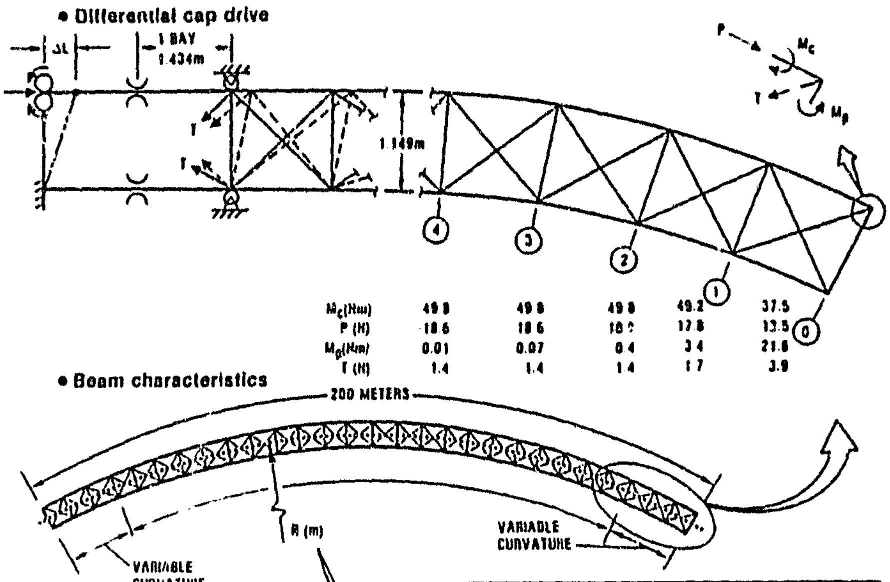


Figure 2-12. Results of environmental impacts evaluation.

2.2.5 CURVED BEAM FABRICATION. An attractive approach to the construction of contoured spacecraft surfaces (e.g., antennas) is the use of curved beams, since they offer the potential for establishing the "net" contour without auxiliary standoffs. In SCAFEDS Part I, a parametric analysis investigated the effects of cumulative cap length mismatch on the tip deflection of 200-meter beam (Reference 2). At that time, the purpose of the analysis was to help drive out requirements for straight beam accuracy control, and it contributed to eventual selection of the internal-feedback/differential-cap-drive control technique.

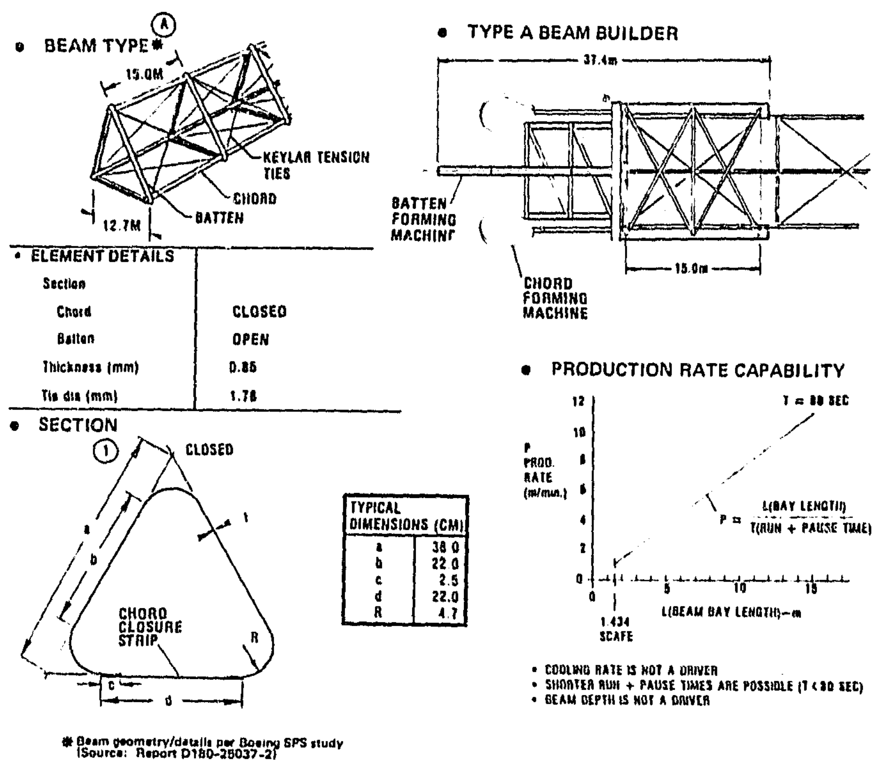
Using this technique it is possible to tailor the length of each cap individually. By driving one cap some increment of length, ΔL, greater (or less) than the other two, it is possible to create curvature of the finished beam, as shown in the upper portion of Figure 2-13. The characteristics of a beam of constant curvature were computed and are shown in Figure 2-13. Because the maximum moment applied to the beam caps occurs at the end posts, the radius of curvature can be decreased by adopting a higher-strength spotweld pattern, by installing two cross-members edge-to-edge, or both.

2.2.6 BEAM BUILDER SCALE-UP. The baseline structural elements used to develop scaled-up beam builder concepts were taken from Boeing SPS work. The largest of three beam configurations used and its associated beam builder are shown in Figure 2-14. The main features of this machine are: (1) it employs six forming machines of a common design; (2) it incorporates a subsystem to store, feed, and join a closure strip for each of the three chord members; (3) it employs a new batten member handler and positioner, because the battens are formed in lieu of being prefabricated and stored in feed clips; (4) its forming machines employ a rolling contact cooling section, in lieu of cooling platens, for minimizing the length of the machine; and (5) it operates on a 24-hour material resupply cycle.



	BASELINE JOINT	OPTIMIZED SPOT PATTERN	DOUBLE END POST	BOTH
M_{MAX} (N m)	21 6	48.7	43.2	91.9
R_{MIN} (m)	169 6	76 2	84.8	39.9

Figure 2-13. Characteristics of a beam of constant curvature.



• ELEMENT DETAILS

Section	
Chord	CLOSED
Batten	OPEN
Thickness (mm)	0.85
Tie dia (mm)	1.78

TYPICAL DIMENSIONS (CM)	
a	38.0
b	22.0
c	2.5
d	22.0
R	4.7

* Beam geometry/details per Boeing SPS study (Source: Report D180-25037-2)

Figure 2-14. Beam builder scale effects determined.

Common forming machines are made possible by selecting a common forming rate while maintaining a total of 80 seconds for the run and pause time cycle. As seen in Figure 2-14 the production rate is proportional to beam bay length. The baseline 80 second cycle time is the time allowed to heat the strip material. A minimum cycle time has not been established.

2.3 ALTERNATIVE ASSEMBLY JIG CONCEPTS

A major task of Part III was to develop assembly jig and fixture concepts capable of constructing six alternative structural configurations depicted in Figure 1-3, using the beam builder as the basic construction tool and the Orbiter as a construction base. The SCAFE beam was the basic element to be used in building these structures. The task produced concept layouts of the structures, assembly jigs and fixtures, and superstructure installations, which were evaluated for Orbiter compatibility and mission and operation impacts. A reference spacecraft concept was developed for each structural shape in order to facilitate the design of superstructure elements and fabrication and assembly sequences. Trade studies of various assembly jig arrangements and assembly sequences resulted in a high degree of commonality between assembly jig concepts. This included not only common subsystem modules but also common assembly jigs for some of the structures. It was found that the square and hex structures could be constructed with the same assembly jig and the cross and 61 m reflector could be manufactured with nearly identical assembly jigs.

2.3.1 SQUARE AND HEXAGONAL PLATFORMS CONSTRUCTION. Two structural configurations, the square and hexagonal platform, using many of the same basic structural components, were designed for compatibility with the platform construction concept. These platforms act as rigid planar periphery frames for a variety of flat panels which require in-plane tension loads to maintain an operational tolerance. The reference spacecraft selected for the square platform structure is a solar array system consisting of eight uniaxially tensioned blankets deployed from cylindrical canisters. The platform basic structure is shown in Figure 2-15. The hexagonal structure, which is not shown, consists of six 64-bay beams joined by similar corner hinged fittings.

The assembly jig concept for fabrication and assembly of the square or hexagonal structures is a common design for both, and incorporates most of the basic features of the original SCAFE "ladder" assembly jig. This includes: (1) cradle, (2) deployment actuator, (3) beam builder deployment and positioning mechanisms, and (4) beam retention, guide and drive mechanisms.

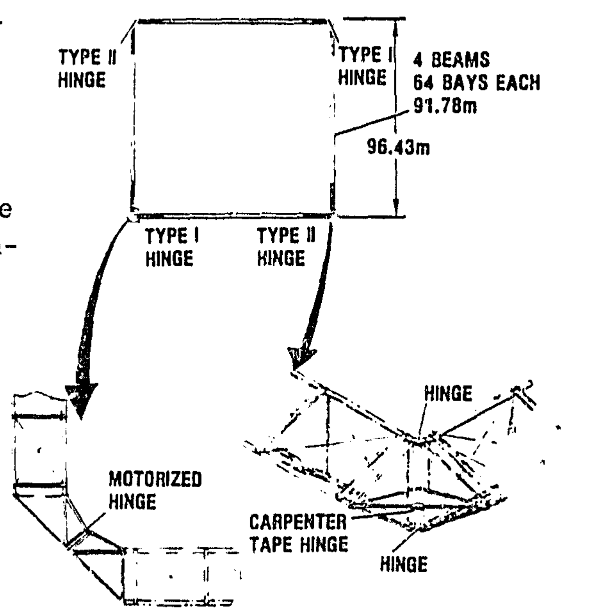


Figure 2-15. Square platform structural assembly.

The unique features of this jig are: (1) two-beam fabrication stations; and (2) two-beam turn-in mechanisms for rotation and translation of beams as they are held by the retention and guide mechanisms (RGMs).

The square and hexagonal structures are fabricated and assembled in the same general sequence using the same basic assembly jig. The sequence for the square structure is shown in Figure 2-16; however, for the hexagonal structure two additional beams and Type II hinges are required. The Type I and II hinge fittings are collapsible for stowage. They are installed by inserting their graphite/polysulfone stub fittings into the ends of the beam caps, and joining with ultrasonic spotwelds. In this case, mission timelines permit use of manual welding techniques.

Deployment of the square structure is accomplished by unlatching the two Type II hinges and activating the motorized Type I hinges as shown in Figure 2-17. The hinge support fitting on the jig reacts bending loads on the swinging beam to prevent torsional loading of the beam held by the RGMs.

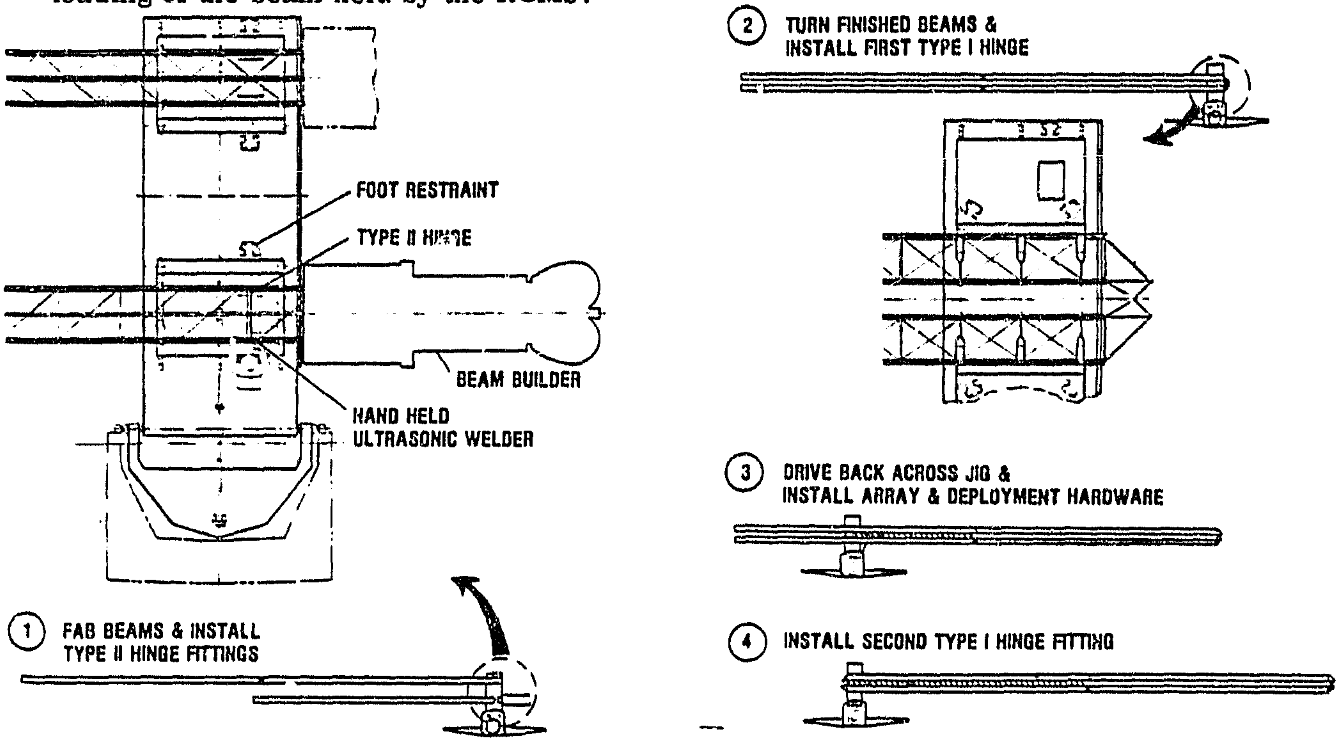


Figure 2-16. Square platform construction sequence.

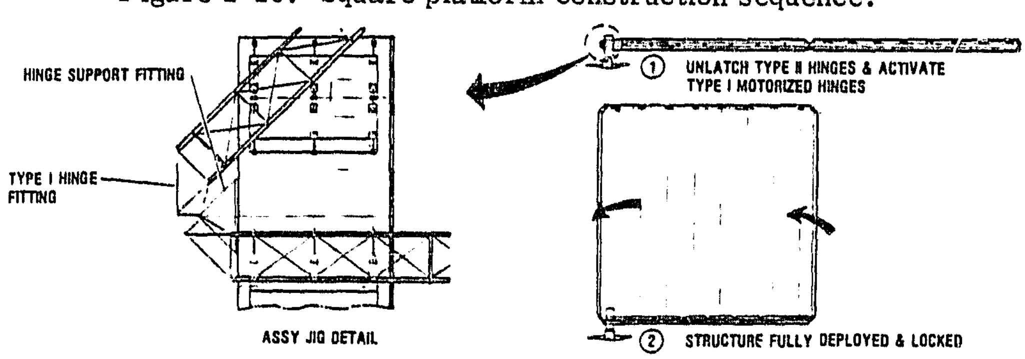


Figure 2-17. Square platform deployment sequence.

With the solar panels encapsulated in canisters mounted along one beam as shown in Figure 2-18, a panel deployment drive individually deploys each panel in sequence.

The reference spacecraft application selected for the hexagonal structure utilizes the hexagonal platform to support a phased array L-band antenna lens as part of a communications satellite concept. The deployment concept of the hexagonal structure is similar to the square structure deployment, except the additional Type II hinge joints require a sequence as shown in Figure 2-19. The lens array would be prefabricated to meet predetermined dimensions of the finished structure. Tension control devices would be incorporated to maintain tautness of the membrane.

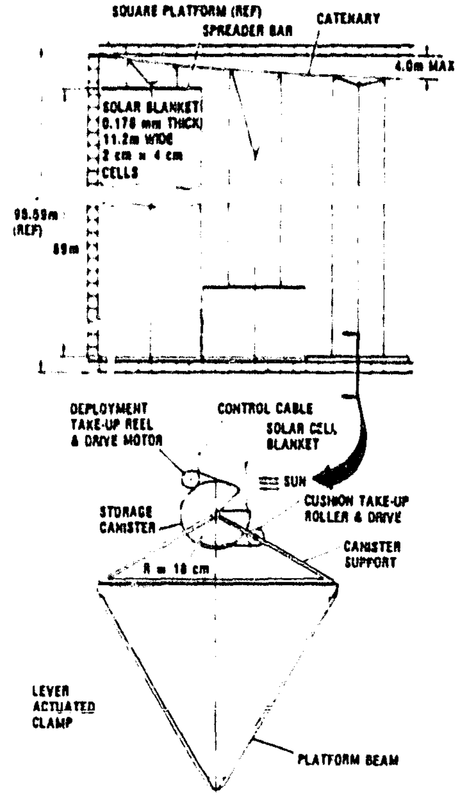


Figure 2-18. Square platform solar array deployment concept.

2.3.2 <u>61m REFLECTOR AND CROSS CONSTRUCTION</u>. The reference spacecraft configuration selected for the 61 m reflector structure is a Cassegrain type antenna, shown in Figure 2-20. The basic structure is an assembly of twelve radial curved beams joined at the center to a prefabricated hub assembly. Foldable, prefabricated gores with integral contoured ribs are attached to the radial beams to form the reflective surface. The subreflector is supported on a tower constructed of three straight beams with prefabricated foldable end fittings, other prefabricated, prepackaged system elements include tower mounting fittings, the subreflector, the subsystem module, and the deployable solar panels.

The assembly jig/beam-builder stowage and deployment scheme shown in Figure 2-21 is similar to that used for the ladder, square and hexagonal structure, except the jig is rotated only 75 degrees out of the payload bay to allow a clearance between the structure and the Orbiter vertical stabilizer.

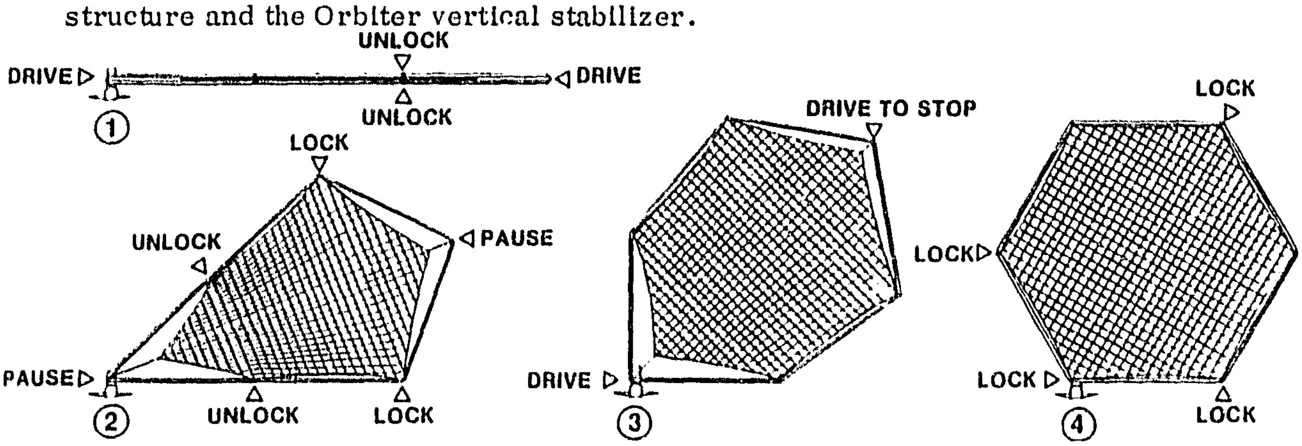


Figure 2-19. Hexagonal structure deployment sequence.

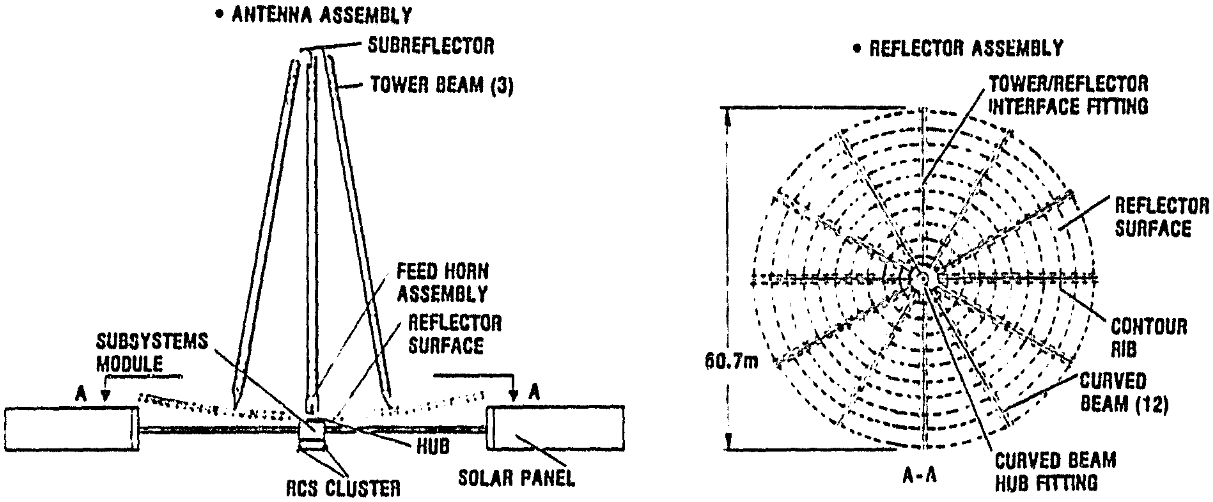


Figure 2-20. 61m reflector structure and spacecraft concept.

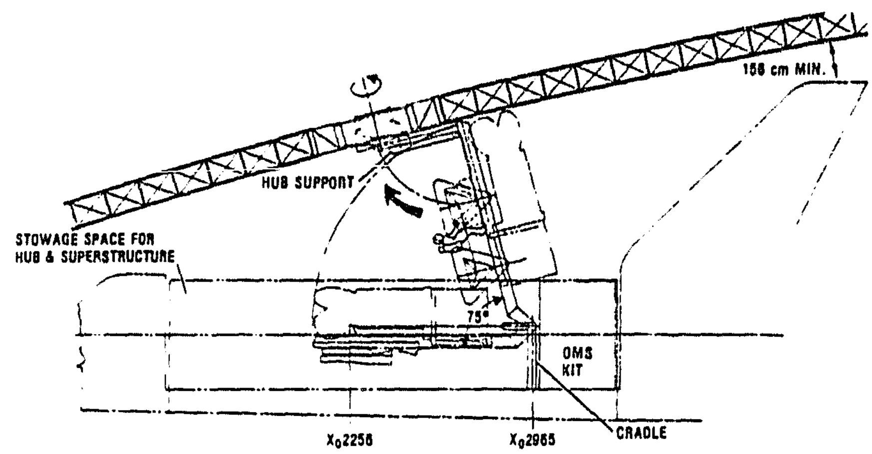


Figure 2-21. 61m antenna construction system and deployment.

The central hub is mounted on an automatic turntable which is supported by an extendable fixture. Two RGMs and a beam drive mechanism are installed on a second rotating fixture. Assembly of the reflector structure is accomplished as shown in the Figure 2-22 sequence. Again, manual techniques are used for installing end fittings.

The technique for fabrication and assembly of the subreflector tower is shown in Figure 2-23. This process requires a special damper-type tower mounting fitting which attaches to a radial beam as shown.

The cross structure and reference spacecraft design concept shown in Figure 2-24 is constructed using a jig which is nearly identical to the 61m reflector assembly jig. In this case, the radial beams connect directly to the central hub, with a common butt joint used for all beam end fitting attachments. The tip antennas are installed using a common attach fitting.

The assembly jigs for the square, hexagonal, cross, and 61m reflector.all employ many of the elements and techniques used on the baseline SCAFE jig. The beam builder remains unchanged from system to system, and the assembly jig deployment equipment

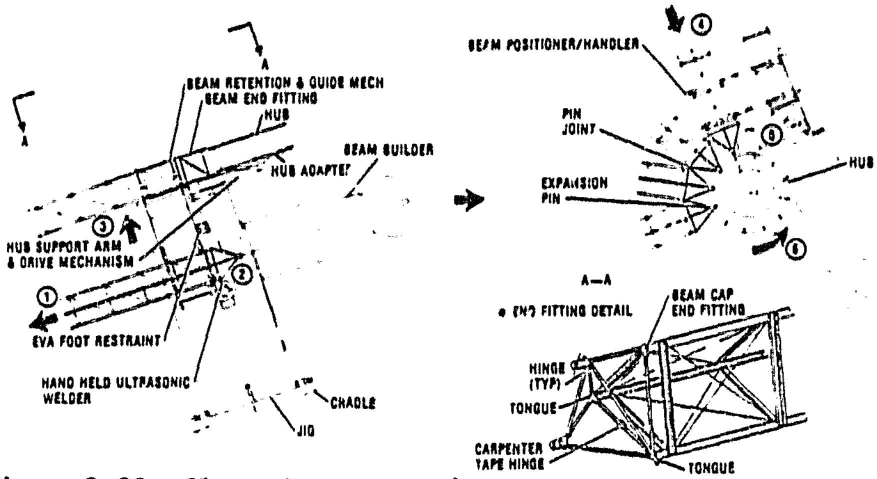


Figure 2-22. 61m antenna curved structure assembly sequence.

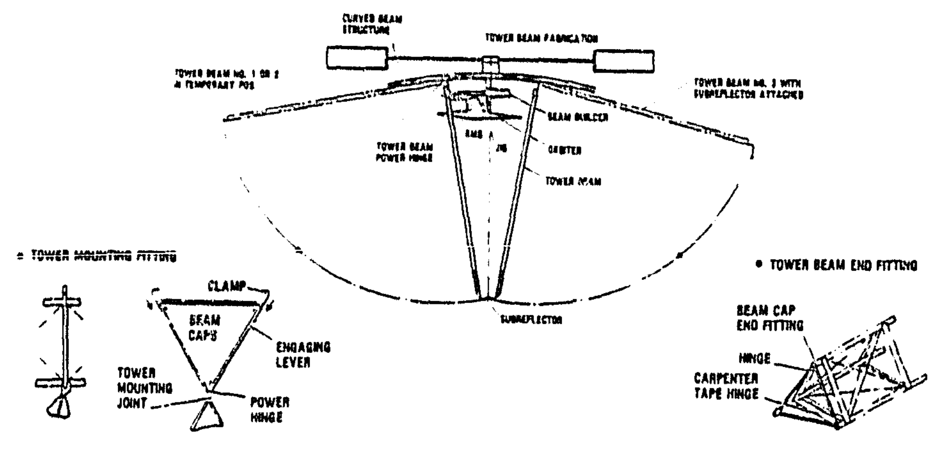


Figure 2-23. Antenna tower construction and installation.

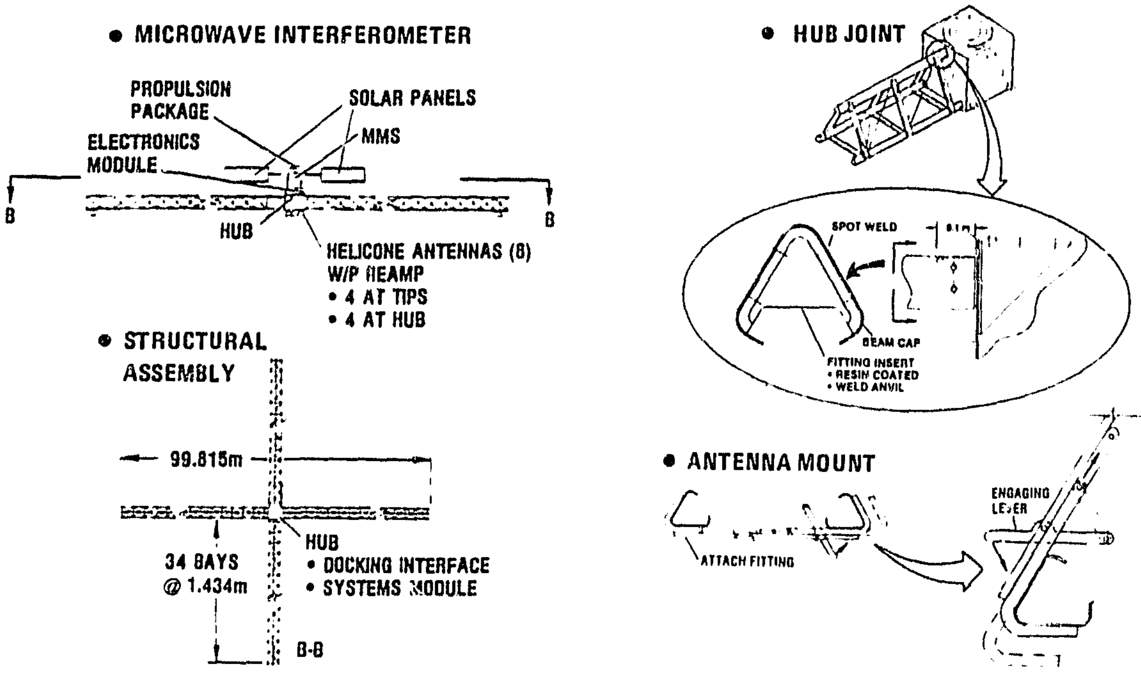


Figure 2-24. Cross construction concept.

is common. This results in a good deal of commonality in the controls system, as shown in Figure 2-25, and much of the basic software is also common.

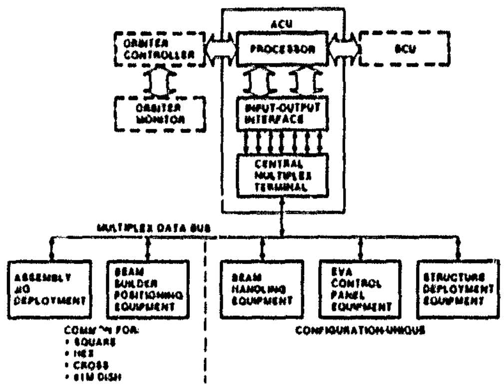


Figure 2-25. Construction systems controls commonality.

2.3.3 TRI-BEAM CONSTRUCTION. The selected large tri-beam structure provides a large rigid platform capable of supporting a multi-user communications system as shown in Figure 2-26. This system would be fabricated in a low earth orbit (LEO) and transferred to a geosynchronous earth orbit (GEO). The fabrication plan for the tri-beam uses baseline beams for cross-member components but a staggered cross-beam arrangement is necessary to eliminate any overlapping or interference problems at the tri-beam cap apexes.

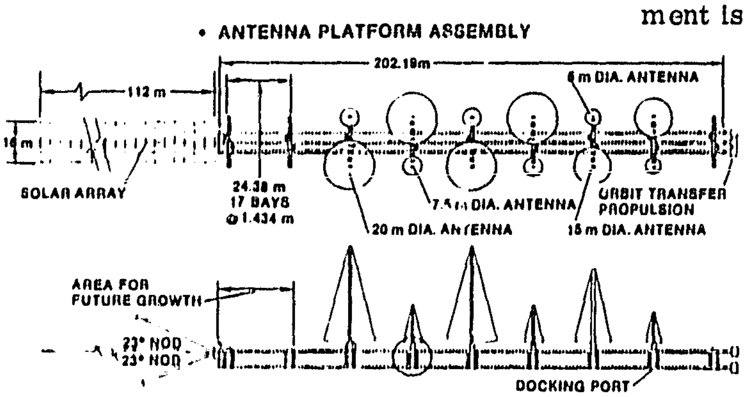


Figure 2-26. Tri-beam structure and spacecraft assembly.

The tri-beam assembly jig, shown in Figure 2-27, represents a significant departure from the basic SCAFE platform assembly jig; however, most of the basic jig subsystem modules are also used in this concept. These include: RGMs and beam drive mechanisms; jig deployment actuator; cross-beam handler mechanism; and beam-to-beam automatic welders. The unique subsystem elements required for this concept are: cross-beam positioner/welder mechanism; beam builder positioner mechanism; beam handling fixture deployment mechanism; forward equipment cradle; and jig structure.

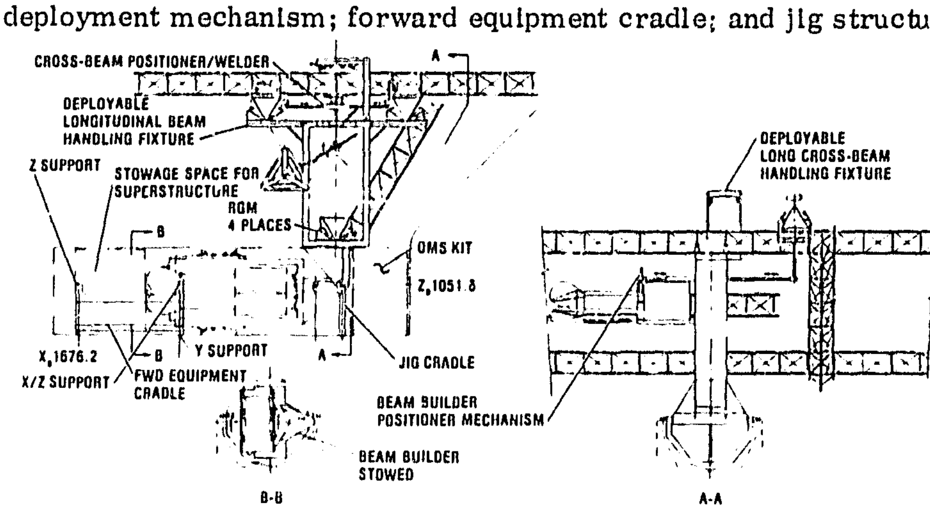


Figure 2-27. Tri-beam assembly jig concept.

2.3.4 <u>500m REFLECTOR CONSTRUCTION</u>. The 500m reflector structural assembly concept, shown in Figure 2-28, is made almost entirely from curved beams produced by the beam builder. Twenty-four radial parabolic curved beams establish the basic dish contour. These radial beams are joined together by circular rib beams through special node joint fittings.

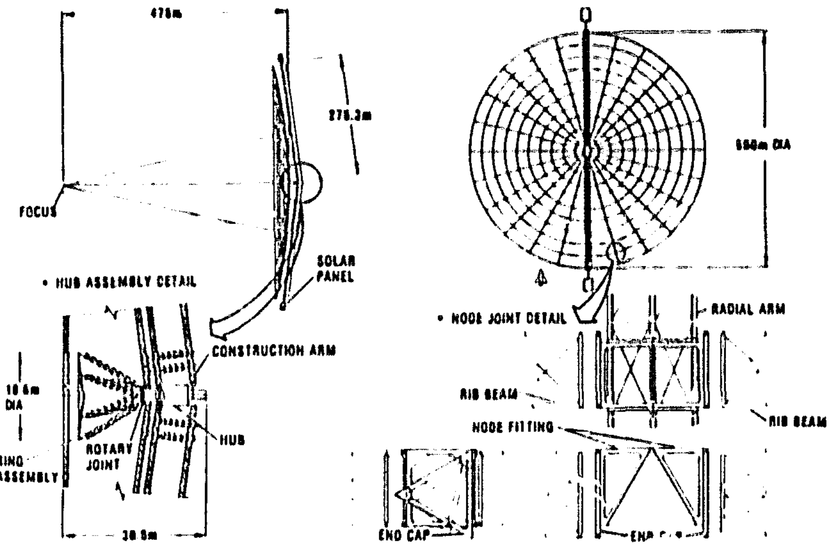


Figure 2-28. 500m parabolic reflector structural assembly concept.

The construction sequence requires a minimum of eight missions. Tri-beams for the construction arms are fabricated using an Orbiter-based assembly jig which converts to the crawler assemblies shown in Figure 2-29. The center fabrication equipment builds and installs the radial beams while the crawlers build and install radial beams automatically. The construction arms rotate with respect to the dish, via a rotary joint, to permit progressive completion of each dish segment. The crawlers also fabricate and install tower beams, and install the reflector surface elements. All jigs and fixtures are removed prior to final deployment of the finished antenna.

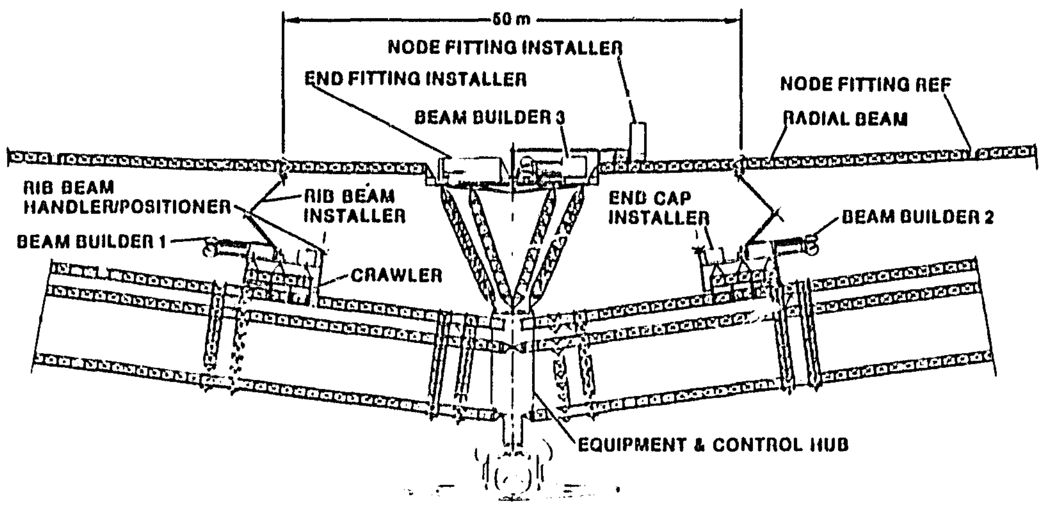


Figure 2-29. 500m reflector construction detail.

2.4 DEVELOPMENT EXPERIMENTS

2.4.1 ULTRASONIC WELDING EXPERIMENT. An ultrasonic welding apparatus which could be used as a Space Shuttle "suitcase" experiment was conceptually designed. The welding experiment shown in Figure 2-30 is designed with these features:

a. Requires minimal space and power. The unit can be installed on a bridge beam in the Orbiter cargo bay and supplied with a 28V dc, 300 watt power supply.

b. Performs all welding, coupon transfer, and process monitoring and control functions automatically.

c. The welding head can be changed as required to produce various weld patterns.

d. Will operate both in air and vacuum. The weld head is automatically temperature compensated.

e. Automatically performs a series of spot welds in flat, two-piece specimens of composite materials.

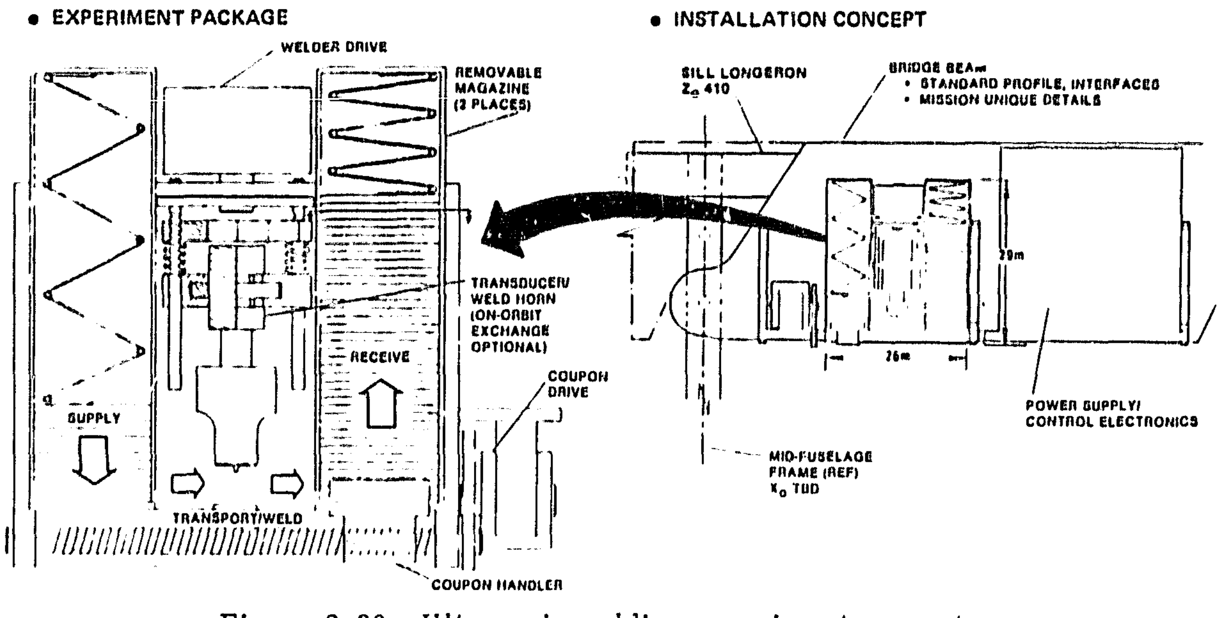


Figure 2-30. Ultrasonic welding experiment concept.

2.4.2 CAP-FORMING EXPERIMENT. A cap-forming "suitcase" experiment was conceptually designed, which would permit the performance of the beam builder cap-forming module to be evaluated in space. The experiment, shown in Figure 2-31, consists of a fully loaded cap-forming machine equipped with a mounting and positioning fixture. A set of storage canisters would be used to retain the in-space formed specimens in a vacuum environment for ground test and evaluation. The cap-forming machine would be equipped with a cap cutter, to permit multiple specimens to be produced automatically.

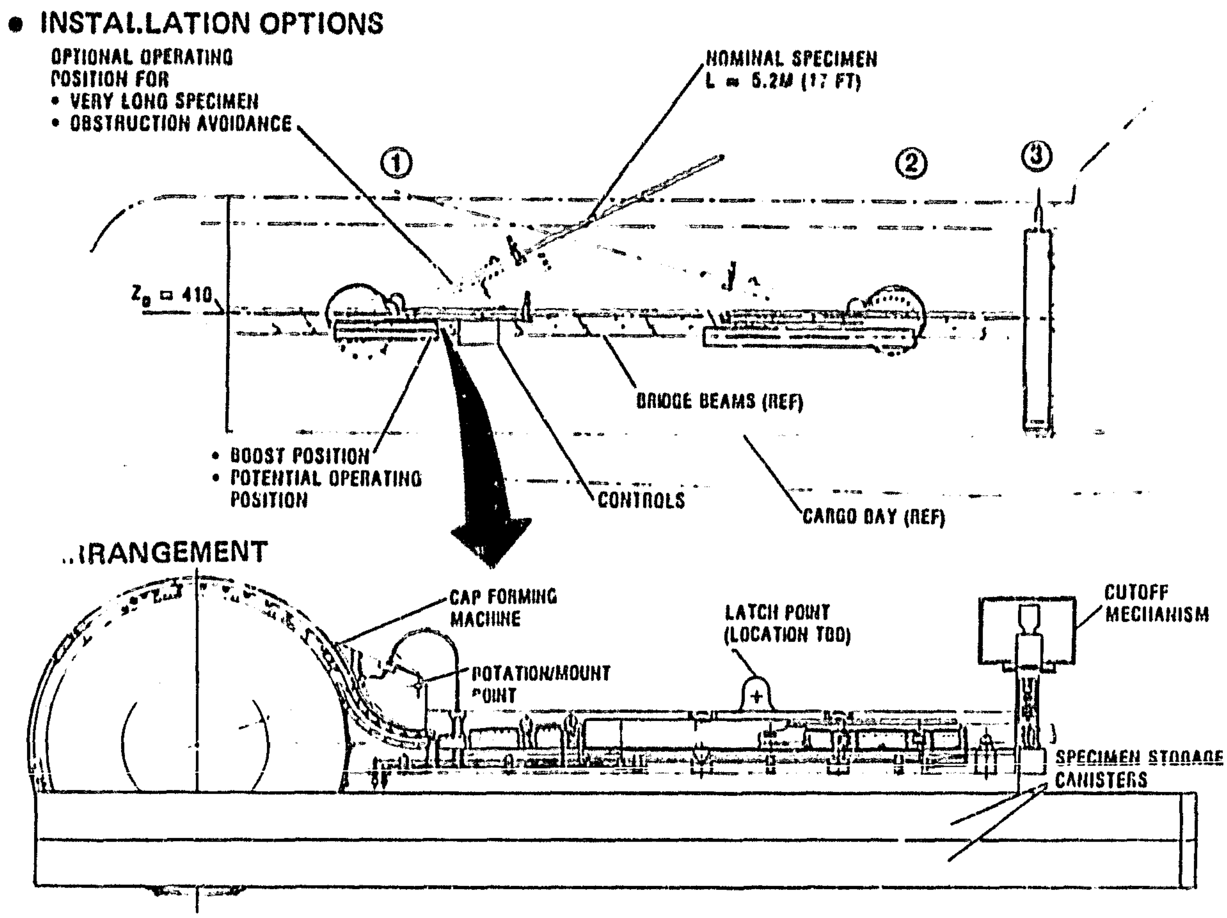


Figure 2-31. Cap-forming experiment concept.

Three options for mounting the experiment in the Orbiter payload bay were examined and are illustrated in Figure 2-31. Options 1 and 2 use bridge beams and can be moved forward or aft or rotated to accommodate prime payload environments. The aft bulkhead provides a third mounting option.

2.5 DEVELOPMENT PLAN AND COST ANALYSIS

2.5.1 REQUIREMENTS UPDATE. As summarized in Figure 2-32, the Part III requirements analysis task involved the updating and expansion of requirements initially defined in Part I/II and collected in Volume III of the Part I/II Final Report. Changes and additions have resulted from three sources: (1) work performed in Part III study tasks; (2) updated ground rules and assumptions; and (3) revision of the Space Shuttle System Payload Accommodations document. The latter were of a bookkeeping nature rather than a technical nature. Certain elements of the Part I/II program baseline, specifically the flight mission spacecraft, assembly jig, and in-orbit operations/timelines, remain unchanged from Part I/II. As before, SCAFE detail requirements have been published as an updated volume (III) of this Final Report.

Continuing programmatic analyses, by both NASA and GDC, led to ground rule changes. Target first mission flight dates slipped from the ones previously planned and a decision has been made to develop only one beam builder end item that will first

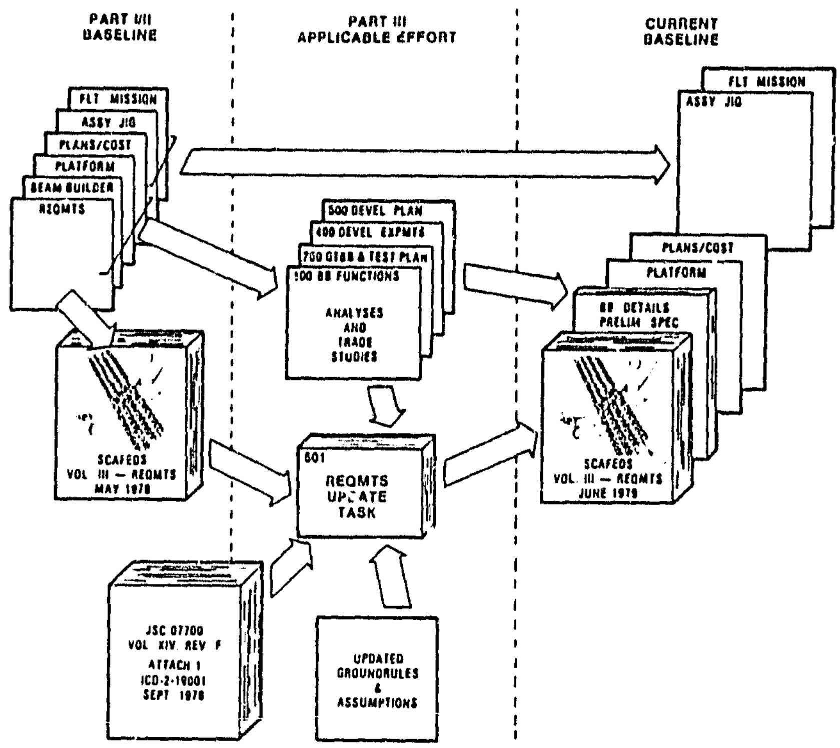


Figure 2-32. SCAFE requirements update.

serve as the ground test development article and then be updated and refurbished for qualification testing and again for the flight mission. Program schedules have been modified accordingly.

The new ground rules for the baseline development plan and cost analysis are given in Table 2-2.

Table 2-2. Baseline development plan/cost analysis ground rules.

- Technology development and program definition prior to phase C/D
- One machine program: GTBB → FTBB
- GTBB is flight qualifiable
  - Modular subsystem development
  - Contains all machine functions
  - Nonflight type components where no compromise to function, fit, or safety
  - No redundancy
- Costs in current constant FY79 dollars with no prime contractor fee
- Total program costs include prephase C/D and phase C/D development/production/operations costs through first flight

2.5.2 SCAFE DEVELOPMENT PLAN. Formulation of a reasonable and complete program schedule involved three steps: (1) preparation of a detailed GTBB development plan; (2) definition of a nominal Phase C/D schedule unconstrained by artifically imposed flight dates; and (3) integration of these into an overall schedule. Analysis of a GTBB development plan showed that developing components and a single subsystem module first as illustrated in Figure 2-33, and then revising the design as necessary before

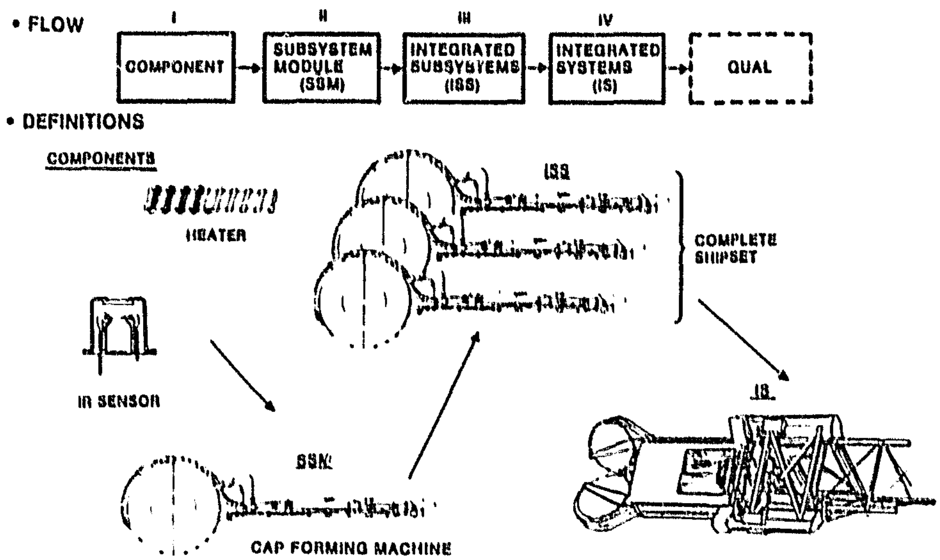


Figure 2-33. GTBB development sequence.

commiting funding for fabrication and testing of the remaining modules in the shipset is a low risk approach. This would take about three years. A Phase C/D program that is relatively tight, but one that would take advantage of development work done on the beam builder, and a Phase B definition study which had been performed to define the assembly jig, the instrumentation for the SCAFE, and the interfaces with the space platform scientific experiments, would take approximately two years and nine months.

The total development process, from the present to flight, for the baseline approach is shown in Figure 2-33. Following completion of this current study, a Beam Builder Technology program would be conducted in parallel with a program to generate a GTBB specification. The result of these activities would support preparation of a competitive RFP for the flight program, with source selection/program start in late 1980.

Combining the baseline GTBB development program and Phase C/D schedule shows that developmental testing of all subsystem modules can be completed before Phase C/D start, that the GTBB demonstration will occur concurrent with CDR, and that the system can be ready for flight somewhat before the second LSSSE flight mission milestone shown in current NASA planning (Figure 2-34). The schedule allows for a three-year development time for the flight experiments, which is moderately tight but attainable based on recent experience.

An alternative plan was investigated. By adopting a higher level of risk, GTBB development can be shortened such that demonstration of the complete machine is accomplished prior to Phase C/D ATP. The major effects of this approach are higher risk and increased initial funding rates but potentially lower total cost.

2.5.3 SCAFE PROGRAM COST ESTIMATE. The preliminary cost estimate for the complete SCAFE program is summarized in Figure 2-35. Costs are presented for: the pre-Phase C/D phases; all of the hardware and tasks associated with program Phase C/D development and test; the refurbishment, modification, and fabrication of the flight

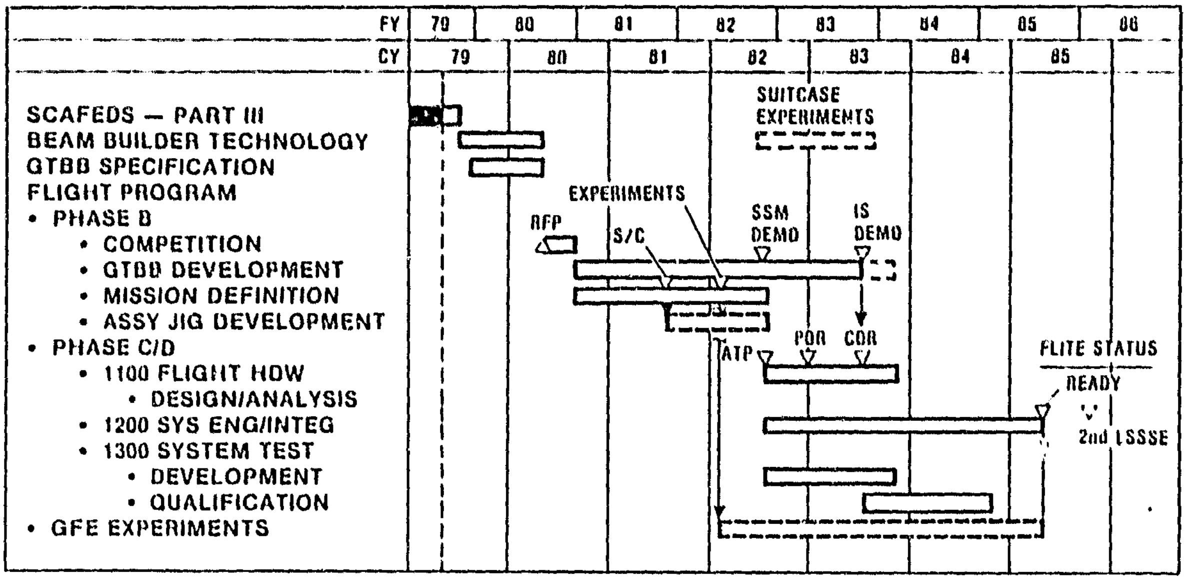


Figure 2-34. Baseline program schedule.

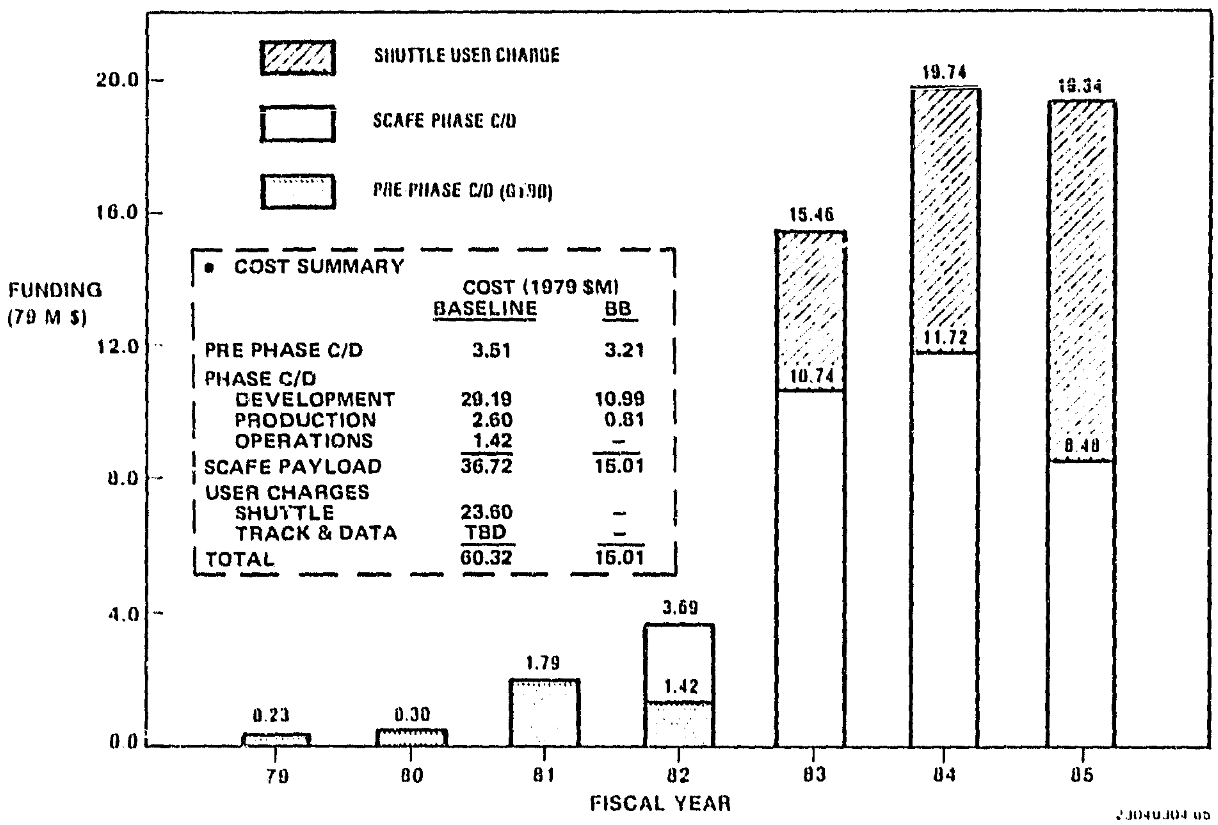


Figure 2-35. SCAFE program funding requirements.

hardware; and the operations activities incurred during the first flight. It was assumed that the Shuttle user charge includes all Shuttle-related activities such as on-line payload installation (OPF), MOC activities, flight crew costs, and other common ground operations/mission operations and activities. Other Shuttle related services such as OMS kits, RMS, and other optional services are added to the Shuttle user charge for

the basic transportation. Potential user charges for tracking and data acquisition (TDRSS, etc.) are carried as separate program-level items.

These estimates represent total cost to customer incurred by the overall program, not just SCAFE prime contractor costs. The costs are estimated in current constant FY 1979 dollars and prime contractor fee is not included.

The estimate included all payload-incurred costs through the first launch (1985) of the fabrication experiment and three months of experiment orbital monitoring and data acquisition. The program estimated is essentially a one-machine program. The GTBB hardware produced during the pre-Phase C/D technology development phase will be updated and refurbished, and will be provided with all additional hardware necessary to serve as the integrated DET article in Phase C/D. The DET will be converted to the DPT article for qualification tests and then to the flight article for the experiment flight. The flight hardware article consists of the DPT ground test article refurbished to flight configuration and standards. The costs for updating the test article are included as recurring production cost.

Annual funding requirements for the SCAFE program are illustrated in Figure 2-35. These funding estimates are shown individually for: (1) the pre-Phase C/D period, which includes program definition and the GTBB technology development phase (beam builder subsystem DET); (2) Phase C/D, which includes completing the development (assembly jig DET and combined beam builder/assembly jig DPT), refurbishment of the DPT test article to flight configuration, and flight experiment prep and operations; and (3) the STS user charge.

3

CONCLUSIONS & RECOMMENDATIONS

3.1 CONCLUSIONS

Principal Part III conclusions are grouped by major category in Table 3-1.

Table 3-1. Study conclusions.

- STRUCTURE/MATERIALS
  - Beam dimensions are unchanged.
  - "Lipped channel" crossmember improves handling and increases load limit.
  - Modified spot weld pattern for crossmember compatibility.
  - New single-ply woven glass/graphite strip material selected. It improves raw material processing, retains key physical/mechanical properties, significantly reduces beam weight, permits common material for cap and cross member, and exhibits lower through-thickness ΔT to enhance temperature control.
- BEAM BUILDER DESIGN
  - Evaluation of payload environmental requirements revealed no major problems.
  - Detrimental environmental effects on subsystems are avoidable.
  - Thermal shroud will prevent thermal distortions of support structure and subsystems.
  - Definition and selection of control and monitoring sensors completed.
  - Common brushless DC motor selected for all beam builder mechanical drives. Dual motor Universal Drive Unit (UDU) for all driven mechanisms except cooling platens, provides redundant drive capability and dual power backup capability.
  - Cooling platen positioning drive mechanism is single failure tolerant.
  - Arrangement of avionics and control equipment improves subsystem modularity.
  - Dual-wire redundant heater elements permit in-air and vacuum operation.
  - Overall cap forming machine length increased 45.7 cm to accommodate revised forming and drive sections.
  - Mass of the fully loaded beam builder has decreased from 3618 Kg to 3404 Kg.
  - New crossmember subsystem design has only two motor drives and provides improved crossmember feed, handling, and positioning.
  - Optical rotary encoders in the cord plyers preclude a large number of position sensors.
  - Small ultrasonic weld head envelopes are readily achieved and further size and weight reductions are possible.
  - Ultrasonic welding process and in-process quality control can be totally automated.
  - Curved beams of constant or variable curvature can be produced by the baseline beam builder.
  - Scaled-up beam builders can produce beams configured for solar power satellite construction. Beam production rates increase in proportion to beam bay length to be produced.
- ALTERNATIVE ASSEMBLY JIG CONCEPTS
  - Baseline SCAFE assembly jig and platform construction system provides basic model for a wide variety of shuttle-borne automated space construction systems.
  - Construction of open polygons and structures having radial beam elements can be accomplished with nearly identical construction systems.
  - Fully automated fabrication of tri beams is possible.
  - Construction of very large space structures like the 500m antenna, will require operation of Space Shuttle to its maximum capacity and capability on multiple missions.
- DEVELOPMENT EXPERIMENTS
  - An automated ultrasonic welding "suitcase" experiment can prove systems reliability, repeatability and weld characteristics in combined vacuum and zero-g with no impact on other payloads.
  - The baseline design fits on a single bridge fitting, requires minimal control interfaces, allows interchangeability of specimens, horns and transducers, and will record all weld parameters.
  - A cap forming experiment can be performed to verify operational characteristics in space environment prior to completion of the Flight Test Beam Builder (FTBB).

- Various options exist for mounting to avoid conflict with other shuttle payloads.
- The forming experiment is identical to a beam builder cap forming module with a cap cutoff module added.
- Storage canisters for formed test specimens are vacuum sealed for post flight evaluation of as-formed condition.

- BEAM BUILDER DEVELOPMENT
  - Nominal development time is required for evaluation and optimization of subsystem modules and system integration and evaluation. This baseline GTBB Development Program provides low risk.
  - A Phase B mission definition study needed to define the spacecraft, assembly jig, mission experiments, and user systems.
  - Total program costs, excluding shuttle user charges, are estimated at \$37.7M including \$3.5M pre-phase C/D development work.
  - Single shuttle flight to accomplish all mission objectives saves \$23.6M by eliminating revisit mission.

3.2 RECOMMENDATIONS

Part III effort has identified several areas in which further activity is recommended. The most significant of these are collected, by major category, in Table 3-2.

Table 3-2. Recommendations.

- BEAM BUILDER TECHNOLOGY
  - Evaluate and optimize functions of cap forming machine to produce operational quality caps.
  - Develop and evaluate variations of the SCAFEDs graphite thermoplastic composite strip material.
  - Investigate and evaluate ultrasonic welding in thermal vacuum and zero-g environment.
  - Investigate high voltage losses into space plasma at LEO in connection with ultrasonic welding.
  - Manufacture prototype triangular truss segment.
  - Prepare test plan and test the prototype truss to determine cap section strength, truss stiffness, dynamic damping, and overall strength characteristics.
  - Prepare materials and weld samples for space environment testing program at NASA/LaRC.
- GROUND TEST BEAM BUILDER DEVELOPMENT
  - Prepare detailed procurement specifications for a GTBB.
  - Prepare necessary design layouts and design analysis to define or verify specifications and control drawing requirements.
  - Prepare Specification Control Drawings for system and subsystem module levels.
  - Prepare detailed statement of work for manufacture, development and test of a GTBB.
  - Prepare Contract Data Requirements List (CDRL).
  - Defer development of heat rejection subsystem to flight system development program.
  - Use staggered system development approach to minimize risk and maintain annual funding levels.
- FLIGHT EXPERIMENT
  - Initiate flight experiment program for space fabricated proof-of-concept. Establish planning ground rules and nominal schedule.
  - Conduct GTBB hardware developments to support flight hardware design and allow conversion to flight configuration within projected costs and schedules.
  - Perform mission definition studies.
  - Conduct assembly jig development.